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Final Report

Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis

Submitted to

Commander
Office of Naval Research
875 North Randolph Street
Arlington, VA 22203-1995

Attention: J. Eckman, Code 322

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Graduate School of Oceanography
The University of Rhode Island

Final Report

Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis

Executive Summary

The research conducted with the funding made available through this grant was from an ONR Departmental Research Initiative (DRI). The objective of the DRI was to better understand Layered Organization in the Coastal Ocean (LOCO). The explicit goal of the DRI was "*To understand the properties of densely concentrated, thin layers of planktonic biota that can occur in coastal ocean environments, and the interacting physical, chemical, biological and optical processes responsible for establishment, maintenance and breakdown of layers.*"

Our research had multiple interlinked objectives. The science objectives were twofold. The first, and most important, task involved describing the abundances and timing of changes in the spatial distribution of secondary producers (zoolankton and micronekton) during the LOCO field program. Several specific study sites in Monterey Bay had been selected during the LOCO group's planning meetings. Measurements at these locations were made in support of our LOCO colleagues' simultaneous efforts to describe fine-scale features in the local ocean physics and to try to better understand the dynamics associated with the formation, maintenance and destruction of thin layers of phytoplankton. When present, thin phytoplankton layers are known to affect the scattering and absorption of light in the upper ocean. We had previously shown that time-depth histories for acoustic scattering layers (zooplankton layers) are often coherent with those observed for thin phytoplankton layers when measured at the same time and place. Grazing by zooplankton can locally modify the toal phytoplankton biomass and create heterogeneity in thin phytoplankton layers. It can also change the thickness and vertical shapes of thin phytoplankton layers. Zooplankton can indirectly affect underwater visibility by changing optical absorption and scattering at different wavelengths by selectively removing particles of different sizes. The sensing methods chosen for describing the zooplankton in the LOCO studies involved the deployment of multi-frequency, high-resolution acoustic sensors on the seabed, looking upward. These sensors used narrow beams and high signal bandwidths, resulting in depth resolutions of 12.5 cm or better. Data rates for complete independent water column profiles were as high as once a minute. The sensors deployed and methods used allowed us to observe evolving patterns in great detail. Those patterns were then compared with similar patterns derived from high-resolution sensors that measured the ocean physics, chemistry, and optical signatures.

Our second science objective was to examine the possibility that some of the acoustic scattering from thin layers of zooplankton that co-occur with thin phytoplankton layers might be due to the presence of O_2 bubbles generated *in situ*. Inverse calculations on measured profiles of acoustic scattering spectra did reveal the presence of numerous small gas bubbles in some thin layers, but not all of the thin bubble layers were associated with thin layers of phytoplankton. As a result of our analyses, we have retained our original hypothesis, but are expanding it to include the possibility that small CH_4 or O_2 bubbles rising from near or on the seabed might be trapped or otherwise accumulated non-uniformly with depth by the fine-scale ocean physics or by the presence of layers of biological organisms, marine algae, detritus (marine snow) or other substances in the water column that originally had a biological origin.

We were able to show that some, but not all thin phytoplankton layers appear to attract zooplankton. This often results in the formation of thin phytoplankton and zooplankton layers that coincide in depth. The usual presumption is that when this happens, grazing folows. It is possible that the formation of thin plankton layers serves to aggregate food resources locally to levels that equal or exceed those associated with such trophic exchange processes as are enabled by the presence of the seasonal chlorophyll maximum and horizontal patchiness. The presence of thin plankton layers may have been especially important in the low food environment encountered in Monterey Bay during the years we occupied stations there for the LOCO program. The low food levels encountered appear to have been the result of a late onset of upwelling along the Pacific Coast off northern California, Oregon and Washington. Had there been little or no aggregation of the food, encounter rates would have been much lower than it was with the presence of the thin layers. This holds for the zooplankton predators as well as for animals higher in the food web, e.g., fish larvae.

Based on our LOCO observations it was very clear that zooplankton behavior can be an important food aggregating mechanism, leading to the diel nighttime formation of thin acoustic scattering layers. Peak levels within these layers greatly exceed average background levels on either side of the layers. In 2005 and 2006 most of the thin phytoplankton and zooplankton layers we observed exhibited reverse diel vertical migration. In those two years this behavior was the dominant process leading to the formation of thin plankton layers. It is also important to note that the zooplankton (mostly *Acartia tonsa*) avoided co-locating with the phytoplankton (mostly the dinoflagellate, *Akashiwo sanguinea*) during the nighttime hours. During the night, biomass peaks for the zooplankton were above and below the thin phytoplankton layer. The diel onset of downward migration by the thin zooplankton layer coincided with declining light levels at sunset, but the upward migration to the surface was completed well before sunrise.

Finally, it has been our experience that physicists and engineers designing new acoustical sensors and systems intended for use by the operational navy often lack critical estimates of various parameters that describe the environment in which the systems must operate. Historically this has been particularly the case when a system is designed to

operate at acoustical frequencies that have not previously been utilized for naval sensors. The availablity of direct measurements of descriptive parameters such as the depth and frequency dependence of acoustic volume scattering strength in a coastal environment during different seasons allows designers to do a better job and operations research engineers to be more accurate when trying to quantitatively assess the eventual performance of such systems (e.g., various sonars, shallow water acoustic modems, control and telemetry systems for AUVs, etc.). Secondary production in the sea can both directly and indirectly affect the levels and statistics of acoustic reverberation. It can also impact the abundance, distribution and character of biological false targets (e.g., the sizes and shapes of fish schools and their distribution in depth). For this reason we have made it a point to measure and report the acoustical data we collected in terms that should useful to the community charged with the design, evaluation, and performance of future naval acoustic systems.

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Graduate School of Oceanography
The University of Rhode Island

Background

The long-term goal of our research continues to be the development of data-based models to predict ecological relationships between the organisms that live in the sea and their physical and chemical environments. Understanding the marine ecosystem sufficiently well to support the development of predictive models is still limited by man's inability to observe life in the sea on scales of time and space that most directly impact individual animals. *In lieu* of having a robust ability to make direct, long-term observations of the animals and their environment *in situ*, much of our knowledge about how they live is inferential. Understanding the distributions and dynamics of all of the trophic levels is critical if we are to eventually acquire an ability to predict such things as the numbers, sizes and morphological characteristics of plankton, fish, marine mammals and benthic organisms which impact naval operations in all ocean areas, including the coastal zone. Similarly, many of these same requirements apply if the fisheries science community is to begin moving towards ecosystem-based management for exploited stocks.

The impact of marine life on acoustic and optical sensors that affect the ability of MCM, ASW and special ops forces to perform their missions have been documented in numerous symposia and meetings. Put succinctly, zooplankton and micronekton control optical properties of interest through grazing on phytoplankton. They also control many of the acoustical parameters that limit the performance of many naval sensors by transferring energy via the food web to trophic levels that scatter sound at frequencies used in operational and future Navy systems. From an ecosystems science viewpoint, if we can understand how phytoplankton and zooplankton scatter or absorb light and sound, then we can also use sensors that make use of optics and acoustics in the characterization of the environment to study the critical components of a marine ecosystem.

Project History

The focus of our work under this grant was to subject acoustical data, collected in Monterey Bay during 2002, 2005, and 2006 to detailed processing and a variety of analyses, compare our results from acoustical sampling with the results obtained by our LOCO collaborators from different suites of sensors, e.g., optical sensors on the Donaghay team's profilers, and to prepare papers for publication.

Our physical and acoustical data were collected under two different contractual vehicles, since the LOCO work spanned the times of retirement for Holliday and Greenlaw from BAE Systems (N00014-00-D-0122/3). Holliday was subsequently employed by the University of Rhode Island and funded to carry out the analyses reported in this document (N00014-07-1-0639). Greenlaw, who had been an integral part of the BAE Systems research team for the earlier LOCO work was retained by URI a consultant and continued to contribute to the acoustical analyses and to the synthesis of the acoustical data and its comparison with the results of our LOCO colleagues.

During the period of this grant, in order to address the goals of the larger ONR Code 322 LOCO DRI, we have routinely shared our data with several of our LOCO colleagues and have examined and distributed selected parts of the data that specifically overlapped or supported their specific scientific interests. Several of our LOCO collaborators have likewise shared data with us. Some of the results from our collaborations have already been published (e.g. Cheriton, et al. 2007; Holliday et al. 2009; Holliday, Greenlaw and Donaghay [in press]). Holliday 2009. We have also included additional results of our collaborations in several co-authored publications cited in the Publications and Presentations section of this report.

Brief Discussions of Selected Observations and Patterns

The acoustical data acquired during the LOCO field periods in Monterey Bay is unique in its temporal and (vertical) spatial resolution. The depth resolutions for our primary acoustic sensors were 12.5 cm. Full water column profiles (*ca.* 22 m) were usually accquired at intervals of minutes. One-minute intervals were used during times when scattering patterns were changing rapidly. Intervals of as long as five-to-ten minutes were employed when the scattering patterns were relatively static, thereby allowing us to conserve battery power and operate the sensors for longer periods between battery changes. The use of multiple acoustic frequencies ranging between 0.165 and 3 MHz enabled estimates to be made of size for organisms in a range that covers small zooplankton (e.g., copepods) through relatively large micronekton (adult euphausiids). By measuring the shape of the scattered acoustic spectrum, assignment of the total scattered acoustical energy could be made to two basic scatterer shapes – one typical of small copepods, and the other typical of more elongate scatterers such as krill. Individual fish and schools of fish were also observed, but the frequencies used did not support making size estimates for those organisms.

By deploying several sensors in the same coastal area with these characteristics, it was possible to discover temporal patterns that revealed how the zooplankton distributions varied horizontally as the fine-scale vertical environment changed. We were able to confirm that some of the patterns extended over horizontal dimensions of several kilometers.

The high acoustical sampling rates in time and depth, along with the use of two-way telemetry, allowed the acoustic scattering observations to be processed quickly so that our LOCO colleagues could use the information as an aid in designing their sampling and instrument deployment protocols. It was also possible to compare changes in zooplankton and micronekton at specific locations with information derived from several kinds of high-resolution optical data collected by our LOCO colleagues. In the end, we were better able to better understand the interactions of phytoplankton, zooplankton, and the constantly changing fine-scale features in their water column habitat.

Measurements of the acoustical scattering were made over a very wide range of acoustic frequencies for periods of weeks-to-months. At times, measured acoustical scattering patterns in depth and time revealed the presence of higher-level organisms in the food web (e.g., individual fish and fish schools). Since multiple measurement stations were occupied during three different years in the same ocean area, we can have some confidence that our measurements are not simply single snapshots of an unusual short-term event. The observed patterns did vary, and the changes observed are also valuable since they reveal information about the range of variation that might be expected in a similar coastal environment.

Our measurements in Monterey Bay during 2005 and 2006 revealed that maximum volume scattering strengths (S_v) in thin acoustic scattering layers often exceeded -30 dB for frequencies between 0.165 and 3 MHz. On occasion the values were even higher, exceeding -20 dB. That these S_v values are higher than have been previously reported in most instances can be attributed to the fact that the sensors used in this work have a vertical resolution of 12.5 cm. Higher spatial resolution allows measurement of high-peak-scattering strength regions that, in lower resolution, would average out with adjacent regions to a lower overall scattering strength. Data from sensors without this amount of depth resolution dominate most of the literature on this topic and have likely led to significant underestimates of the maximum volume scattering levels within very thin layers of zooplankton.

The thin acoustic scattering layers observed on the narrow shelf in the northeastern corner of Monterey Bay near Aptos, CA were mostly attributed to the vertical distribution of small zooplankton and micronekton. The zooplankton biomass in the northeast corner of Monterey Bay was quite low in each of the three years of the LOCO field program, but it was lowest in 2005 and 2006. The low abundances have been attributed to a late onset of upwelling favorable winds and low levels of nutrients in the surface waters of the California Current (Pierce et al., 2006; Mackas et al., 2006). Since zooplankton biomass was low, the heterogeneous aggregation of food in patches and layers may have been even more critical than it is when food is more abundant.

In 2002, most of the vertical depth distributions of the observed layers were correlated with thin vertical distributions of optical fluorescence usually attributed to the presence of the chl-a in phytoplankton. Multispectral optical scattering sensors were intentionally deployed by Donaghay's URI team in the same locations and at the same times as acoustic data were collected. Those sensors were used to find and characterize the phytoplankton thin layers (Holliday et al. 2009; Holliday, Greenlaw, and Donaghay [in press]). In these cases, there is usually a presumption that the zooplankton and micronekton are grazing on the phytoplankton. Most of the thin layers observed that year appeared to be associated with layers of chl-a fluorescence. The vertical dimensions of the layers observed in 2002 varied from *ca.* 0.5 m to *ca.* 2 m, but varied in thickness and depth throughout the field period, occasionally disappearing at a particular mooring site entirely, only to reappear later. Most were observed in mid-water, but a few persisted at depths only a few meters above the seabed. Their vertical modulations largely

varied with periods typical of those expected for internal tides and internal waves. While a few patterns were observed which may have been associated with vertical migration, those patterns did not seem to dominate the observed changes in layer depths with time.

When our acoustical data from 2005 and 2006 were compared with the physical, optical and direct sampling data acquired our LOCO colleagues, the observations of thin layers over days-to-weeks strongly suggest that zooplankton behavior may have played a very significant role in creating a complex depth-time history for acoustic scattering layers. During daylight hours most of the water column's biomass was located within *ca.* 10-20 cm of the sea's surface, as measured acoustically with an uplooking TAPS. Downward migrations of particles having spectra consistent with that expected from zooplankton and micronekton appeared to be triggered by rapidly decreasing light levels near sunset, but some secondary migrations also occurred later in the night. Within *ca.* 30 minutes after sunset most of the water column zooplankton biomass near the sea surface quickly became concentrated in a small number (e.g., two or three) of sub-meter thick scattering layers. Those layers then exhibited patterns of reverse vertical migration (from near the sea surface to mid-water, or deeper). In each case, there was a limiting depth at which the migration downward ceased for some of the acoustical scatterers. When this depth was reached, the organisms maintained their positions near a thermocline or pycnocline as it moved vertically with the internal tides or internal waves. The upward migration of a layer, or sometimes the gradual upward dispersal of organisms that had been in a discrete thin layer during part of the night to the surface from mid-water depths, was often completed well before sunrise, even as early as 0300 PDT (local time). Sunrise was typically at *ca.* 0630 PDT during the LOCO field seasons.

Our joint analyses revealed that a thin layer of dinoflagellates (dominated by *Akashiwo sanguinea*) also migrated to approximately the same depths at sunset each night, returning to the surface by daybreak. However, instead of concentrating at the peaks of the thin chl-a fluorescence profiles, the acoustic (i.e, the zooplankton, dominately *Acartia tonsa*) scattering layers were found to have distributed themselves at the upper and lower boundaries of the thin phytoplankton layer after it reached its depth limit for the night (also the location of the nutricline). Limited by the available technology for collecting water samples from sub-meter thick layers in a field of internal waves that sometimes moved the pycnocline through half of the water column's depth in tens of minutes, we were unable to collect zooplankton and examine their stomach contents. However, observed depth-time profiles suggest that the zooplankton and micronekton were avoiding at least some of the thin layers of phytoplankton, foraging on lower densities of diatoms above or below the chl-a maximum instead of co-locating at night with more abundant thin layers of dinoflagellates when potentially toxic species were present.

Finally, volume scattering spectra consistent with the presence of micron-size bubbles sometimes characterized a part of the scattering from thin zooplankton or phytoplankton layers. Our observations were consistent with at least two possible sources of bubbles and two different processes that could give rise to aggregations of bubbles in these layers.

Although additional research is needed in order to fully understand the formation of gaseous bubble layers in the upper water column, our LOCO data lead us to the following hypotheses: Either O_2 (photosynthesis by benthic algae) or CH_4 (methane, from organic decay), in or on the seabed, can create tiny bubbles (a few microns in diameter), some of which may grow, break loose from the seabed, and rise through the water column. Enroute to the surface, the bubbles expand and they can be trapped, delayed or accumulated non-uniformly at depths occupied by thin layers of phytoplankton, marine snow (organic detritus), or layered organic exudates of plankton. They may also scour the water column for some organic compounds. Photosynthetic generation of O_2 in quantities sufficient to cause supersaturation of the upper water column was common during the LOCO field periods. In this O_2-supersaturated environment, especially given the large numbers of nucleation sites in thin phytoplankton layers, along with the presence of moderate values of turbulence, could create conditions that would lead to the formation of O_2 bubbles and lead to enhanced acoustic scattering in thin layers. If they grow *in situ*, some of these bubbles could also rise towards the surface if their buoyancy is sufficient, adding to any bubble flux that might be originating at the seabed. While we cannot rule out the possibility that other processes are also present, the acoustic data collected are consistent with the presence of both of these processes.

Summary of Key Results

The most important results of this work have been documented in the publications listed. A few observations that we consider to be especially important are highlighted here for ease of reference.

- Thin acoustic scattering layers are common features in the coastal ocean, having been observed on both US coasts and in the Gulf of Mexico.

- Thin acoustic scattering layers may persist at a particular location for times varying from hours to weeks.

- Most thin acoustic scattering layers are associated with vertical structure in concentrations of zooplankton or micronekton.

- While thin acoustic scattering layers have not yet been extensively studied in deep, blue water ocean areas or in shallower water on the continental shelves, acoustical data collected with lower resolution sensors used in a cast mode suggest that they are also common features in the upper water column in offshore locations. A reexamination of cast-mode volume scattering data from those sensors revealed numerous scattering peaks that are probably due to the presence of thin layers of zooplankton and micronekton. As with the data from higher resolution sensors, those layers were often associated with small gradients or features in the thermal, salinity, or density structure of the water column (e.g., Holliday and Pieper 1980). Working on the assumption that thin phytoplankton layers are a

concentrated source of food that exceeds average background abundance levels of prey for copepods and micronekton in offshore waters, our conclusion regarding the probable presence of thin zooplankton layers offshore is consistent with the observation of a widespread distribution of optical (phytoplankton) scattering layers detected in numerous offshore locations with lidar (Churnside and Donaghay 2009).

- New methods of deploying the kinds of sensors used in the LOCO research will be required before thin acoustical scattering layers can be fully examined in deep water environments. These methods will have to eliminate, or at least greatly reduce, the coupling of today's measurement platform's vertical motions to sensors that collect the acoustical and physical data when deployed in a cast-mode. Near-neutrally buoyant sensor platforms such as those used by Percy Donaghay (URI) and Tim Cowles (OSU) are possibilities, especially if coupled with a sensor such as the Wide-band, High-frequency Acoustic Profiling System (WHAPS). In past efforts however, high levels of electrical interference in the data communication packages onboard these profilers have seriously compromised the signal-to-noise ratio for the WHAPS. If offshore investigations of thin zooplankton layers are to succeed, those engineering problems will have to be successfully addressed.

- Zooplankton thin layers often co-occur with thin phytoplankton layers.

- Zooplankton sometimes avoid thin phytoplankton layers, creating thin layers of acoustic scattering above, below, or both above and below a thin phytoplankton layer. This behavior is neither rare or unusual (Holliday et al. 2003; Holliday, Greenlaw and Donaghay [in press]).

- Zooplankton often migrate vertically at dusk, creating thin acoustic layers in the water column. These layers often stop migrating at or near specific thermoclines or pycnoclines and follow them closely for hours. Both normal (from deeper waters toward the surface) and reverse (from near the surface downward) vertical migrations have been observed. In the case of reverse migration, the layers sometimes disperse and move upward long before sunrise. This suggests that some migrations are terminated by the time of satiation rather than by light. Similar, albeit slightly less convincing patterns of migration back to the seabed have also been observed for migrators that swim up into the water column from the seabed at dusk. Additional analysis of existing data sets might well turn up additional examples of this kind of behavior. If so, such behavior may be as common as upward migration before sunset for the daytime surface dwelling plankton. Vertical migrators that form thin acoustic scattering layers do not necessarily all start moving either up or down at the same time. In some cases, we have observed thin acoustic scattering layers being forced upward upward by a shoaling pycnocline or the intrusion of a different water mass at midwater depths.

- While less numerous in our LOCO data set than are thin layers with scattering spectra that can be explained by the presence of only zooplankton and micronekton, thin acoustic scattering layers were also observed that have multi-frequency spectra which can be best explained by the presence of zooplankton, micronekton, and very small bubbles (1 to 50 microns in radius). We suggest two hypotheses: 1) bubble layers may be generated *in situ* within thin layers of zooplankton and phytoplankton when the water becomes supersaturated with oxygen because of photosynthesis by the phytoplankton in the layer, and 2) rising bubbles may become trapped and aggregated at the depths of thin layers with a biological origin (e.g., marine snow), or at physical boundaries such as sharp density gradients, as they rise from below. We have previously observed bubbles in the water column that are clearly the result of natural methane seeps (e.g., off Coal Point at Santa Barbara, CA). We have also observed small bubbles, possibly the result of decay processes on the seabed, rising towards the surface in West Sound, Orcas Is., WA. Further, based on laboratory studies, we have suggested that under good lighting conditions, e.g., clear water at depths up to *ca.* 20 m, small bubbles of oxygen may be generated by photosynthesis in the top few millimeters of shallow, sandy seabed (Holliday 2007 and Holliday 2009). Additional studies will be needed to fully understand the mechanisms whereby thin bubble layers can be created in the sea, and their frequency of occurence.

Publications and Presentations

In addition to the annual progress summaries provided for each year's ONR Program Summaries (see Appendices A1, A2, B and C), the following publications and presentations were supported by funding provided under this award or relied on the results of the work by virtue of analysis methods or software developed as a result of our involvement in the LOCO program of research.

Journal Articles

Anderson, J. T., Holliday, D.V., Kloser, R., Reid, D. G., and Simard, Y. 2008. Acoustic seabed classification: current practice and future directions. ICES Journal of Marine Science 65: 1004-1011.

Cheriton, Olivia M., Margaret A. McManus, D.V. Holliday, Charles F. Greenlaw, Percy L. Donaghay, and Tim Cowles. 2008. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the west coast of the U.S. Estuaries & Coasts 30(4): 575-590.

Holliday, D.V., P.L. Donaghay, C.F. Greenlaw, J.M. Napp, and J.M. Sullivan. 2009a. High-frequency acoustics and bio-optics in ecosystems research. ICES Journal of Marine Science 66: 974-980, doi:10.1093/icesjms/fsp127.

Holliday, D.V., C.F Greenlaw and P.L. Donaghay. [accepted, 2009b]. Acoustic scattering in the coastal ocean at Monterey Bay, CA USA: Fine-scale vertical structures. Continental Shelf Research.

Peer-reviewed Cooperative Research Reports, Symposium Proceedings, and Chapters in Books

Anderson, John, Van Holliday, Rudy Kloser, Dave Reid and Yvan Simard (Eds.). 2007. Acoustic Seabed Classification of Marine Physical and Biological Landscapes. ICES Cooperative Research Report, Rapport des Recherches Collectives, No. 286. 183 pp.

Anderson. John T., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard. 2007. Chapter 10: Future directions for acoustic seabed classification science. In Acoustic Seabed Classification of Marine Physical and Biological Landscapes. John T. Anderson, Ed., D.V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp.139-146.

Holliday, D.V. 2007. Chapter 2: Theory of sound scattering from the seabed. In Acoustic Seabed Classification of Marine Physical and Biological Landscapes. John T. Anderson, Ed., D.V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp. 7-28.

Holliday, D.V. 2009. Technology for Evaluating Marine Ecosystems in the Early 21st Century. Chapter 17 in The Future of Fisheries Science in North America, Beamish, Richard J. and Rothschild, Brian J., Eds. Springer-Verlag Fish & Fisheries Series, Vol. 31: 293-311, doi:10.1093/icesjms/fsp127.

Selected Abstracts and Invited Presentations

Holliday, D.V. and C.F. Greenlaw, Patterns in Fine-Scale Vertical Distributions of Zooplankton, Ocean Sciences Meeting, Orlando, FL, (Abstract ID: 2518), Spring 2008.

Holliday, D.V. , C.F. Greenlaw, P.L. Donaghay and J.M. Napp, High-frequency Acoustics in Ecosystems Research, Keynote Address at the Symposium on the Ecosystem Approach with Fisheries Acoustics and Complementary Technologies, Bergen, Norway, 16-20 June 2008.

Related Projects

Our work on the final phase of LOCO "thin layers" work was funded under this contract, however over the last several decades the work that led up to the LOCO program involved cooperative efforts by numerous scientists from several institutions. The larger "thin layers" project was a cooperative research effort involving scientists and technical

staff from BAE Systems (Holliday, Greenlaw, McGehee, and Kleinwaks); the University of Rhode Island) (Donaghay, Rines, Dekshenieks, Miksis, Smith, Gifford, McFarland, and Graff); SubChem Systems (Hansen, Egli); Johns Hopkins University (Osborn); the University of Hawaii (Steward, Woodson); the University of Massachusetts (Goodman, Wang, Luebke, Yarmac); Oregon State University (Cowles, Sullivan, Zaneveld, Benoit-Bird, Waluk); the University of Washington (Perry); UC Berkeley (Stacey); WHOI (Fratantoni); Stanford (Steinbuck); MBARI (Ryan); WetLabs (Freeman); California Polytechnic State University (Moline); the Naval Undersea Warfare Center (Levine); the Naval Research Laboratory / Stennis Space Center (Weidemann); NAVAIR Patuxent River (Concannon, Prentice); the University of Southern California (Pieper); and the University of California at Santa Barbara (Alldredge, MacIntyre, Case, Herren).

In addition to providing data to interested LOCO Principal Investigators, some of our data were also provided to Y. Chao at CalTech, JPL to allow him to initialize some of his forecasting models for a large ONR sponsored research project that followed the LOCO work in Monterey Bay in 2006.

The affiliations given are those that were current at the time of the cooperative effort. Dekshenieks (McManus) first moved from URI to UC Santa Cruz and she is now at the University of Hawaii. Perry and Jumars were at the University of Washington and are now at the University of Maine. Miksis (-Olds) is now at Penn State. We apologize in advance for what we are sure will be unintentional omissions in our list of collaborators given above.

Acknowledgements

John Ferreira and Larry Bird (both at MBARI) greatly helped us with some emergency machining services at critical times. John Ryan (MBARI) provided a useful quick look, pseudo-true color image from the MODIS Airborne Simulator during the LOCO field period in 2006. He also provided access to data from MBARI's AUV during the LOCO project. Steve Ramp (NPS) provided information on SST, wind and surface chl-a distributions during a special overflight in July 2006. Our thanks also go to Jeff Paduan and Mike Cook (both at NPS Monterey) for making their CODAR data available to the LOCO PIs in a very timely and useful manner.

Small boat support was ably supplied by Captains Jim Christmann (R/V Shana Rae from Monterey Canyon Research Vessels, Inc.); Mark Mertz (R/V Relentless from TEG Ocean, Inc.); and John Douglas (R/V Sheila B from California State University at Moss Landing). UCSC's R/V Paragon supported some of the work in 2002 and 2005.

References

Cheriton, Olivia M., Margaret A. McManus, D.V. Holliday, Charles F. Greenlaw, Percy L. Donaghay, and Tim Cowles. 2007. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the west coast of the U.S. Estuaries & Coasts 30(4): 575-590.

Churnside, J. H. and Donaghay, P. L. 2009. Thin scattering layers observed by airborne lidar. ICES Journal of Marine Science, 66(4): 778–789, doi:10.1093/icesjms/fsp029.

Holliday, D.V. 2007. Theory of sound scattering from the seabed. Chapter 2 in ICES *Cooperative Research Report on Acoustic Seabed Classification*. John Anderson, Van Holliday, Rudy Kloser, Dave Reid and Yvan Simard (Eds.). ICES Cooperative Research Report, Rapport des Recherches Collectives, No. 286: 7-28.

Holliday, D.V. 2009. Technology for Evaluating Marine Ecosystems in the Early 21st Century. Chapter 17 in *The Future of Fisheries Science in North America*, Richard J. Beamish and Brian J. Rothschild, Eds., Springer-Verlag Fish & Fisheries Series, Vol. 31: 293-311, doi:10.1093/icesjms/fsp127.

Holliday, D.V., P.L. Donaghay, C.F. Greenlaw, J.M. Napp, and J.M. Sullivan. 2009. High-frequency acoustics and bio-optics in ecosystems research. ICES Journal of Marine Science 66: 974-980, doi:10.1093/icesjms/fsp127.

Holliday, Dale V., Percy L. Donaghay, Charles F. Greenlaw, Duncan E. McGehee, Margaret M. McManus, Jim M. Sullivan and Jennifer L. Miksis. 2003. Advances in defining fine- and micro-scale pattern in marine plankton. Aquatic Living Resources 16(3): 131-136.

Holliday, D.V., C.F Greenlaw and P.L. Donaghay. [in press]. Acoustic scattering in the coastal ocean at Monterey Bay, CA USA: Fine-scale vertical structure, Continental Shelf Research.

Holliday, D.V. and R.E. Pieper. 1980. Volume scattering strengths and zooplankton distributions at acoustic frequencies between 0.5 and 3 MHz. J. Acoust. Soc. Am. 67: 135-146.

Mackas, D.L., Peterson, W.T., Ohman, M.D., Lavaniegos, B.E., 2006. Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005. Geophysical Research Letters 33, L22S07, doi:10.1029/2006GL027930.

Pierce, S. D., Barth, J.A., Thomas, R.E. and Fleischer, G.W. 2006. Anomalously warm July 2005 in the northern California Current: Historical context and the significance of cumulative wind stress, Geophysical Research Letters 33, L22S04, doi:10.1029/2006GL027149.

Appendix A1: Annual Progress Report for 2007 (Phase I)

Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis - I

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LONG-TERM GOALS

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at the scales that control how they live, reproduce, and die.

OBJECTIVES

Our near-term objectives during FY 2007 were focused on completion of our 2006 field work. Working with researchers from several different institutions, we have been studying layered organization in the coastal ocean (LOCO). Our most recent field project involved deploying, and maintaining an array of oceanographic sensors at a fixed shallow water site in the northeastern corner of Monterey Bay, CA during the late summer and early fall of 2006. Our first objective was to make available to the LOCO research team as much information as we could in near real-time regarding the presence of thin mesozooplankton layers and their vertical location in the water column. Rapid access to these data allowed LOCO team members to make informed decisions regarding their own sampling protocols as they collected data describing other factors that may influence the growth, lifetime and decay of these thin vertical biological structures. As a secondary objective, we deployed

several advanced acoustical sensors for which we did not require real-time access to the data. By increasing the number of frequencies at which acoustic backscattering was measured, one of these sensors improved the size resolution we could achieve in describing the mesozooplankton. We also deployed two sensors with the intent of detecting very small gas bubbles. One was used to examine depths at which thin phytoplanton layers were present in water column, and the other was used to study the top few mm of the shallow, sandy seabed. We were testing a hypothesis that photosynthesis could create conditions that would lead to the formation of small bubbles on the phytoplankon in thin layers. Alternatively, if such bubbles were formed in the top few mm of the seabed, broke loose and rose through the water column, they would necessarily have to pass through any thin layer that was present. If such bubbles adhere to phytoplankton cells, strands, mats, or they become embedded in marine snow, then bubbles from either source might act to slow the natural sinking process that removes marine algae from the euphotic zone. The same sensor is useful in examining the water column for depths where larval, swimbladder-bearing fish aggregate.

Both of the BAE Systems principal investigators involved in LOCO retired during the first half of FY 2007. They are continuing this project, participating in the ongoing LOCO data synthesis work under a grant to the University of Rhode Island (URI). This report covers the period from October 2006 through Feburary 2007. Progress from April 2007 through the end of FY 2007 is covered in a companion report for the grant to URI.

APPROACH

During the late summer and early fall of 2005 and 2006, very thin layers of phytoplankton, zooplankton, nutrients, and physical structure were studied by a part of the LOCO research team at several closely spaced shallow, near-shore stations in northeastern Monterey Bay. Other team members examined larger scale horizontal distributions and temporal thin layer patterns in deeper water nearby, while still others collected plankton and made measurements of turbulence and various optical properties of the water column. Our part of this research involved the deployment of several acoustic sensors on the seabed. Some of these sensors were employed as up-looking multiple-frequency echo sounders in this study (Fig. A1-1). In order to gain some idea of the spatial extent and temporal coherence of thin layer structures, our instruments were placed *ca.* 100 m apart in an array of other LOCO sensors near the 20 m contour just off Aptos, CA.

The acoustic frequencies used in one of the sensors, the TAPS-6, were 0.265, 0.420, 0.700, 1.100, 1.850 and 3 MHz. These frequencies have previously been shown to span critical structure in the volume scattering strength spectrum of small zooplankton (Holliday and Pieper 1980). This allows one to estimate scatterer sizes and abundances above the sensor as a function of depth and time (Holliday 1977). Thin layers were tracked in depth as they responded to external physical stimuli (e.g., light, the passage of internal waves, tidal forcing) and plankton behavior was observed as the layer moved vertically, presumably in search for food (e.g., phytoplankton or microzooplankton). We

have also observed what appears to be avoidance of particular depths when various toxins are present in the phytoplankton (e.g., harmful algal blooms (HABs).

Figure A1-1: A TAPS-6 acoustical sensor is shown prior to its deployment at a station ca. 3.5 km SSW of Aptos, CA, near the 20 m depth contour. In this cage, a six frequency TAPS is mounted vertically (black cylinder). The LOCO sampling protocol required the TAPS to be configured as an up-looking echo sounder. A spar buoy can be seen floating in the distance. Data and power are transferred to a two-way VHF radio in the buoy via an electrical cable connected to the TAPS. Several key system parameters are programmable and were controlled from a shore station as needed.

Observations can also be made of the aggregation of predators (e.g., fish) on thin layers, although a higher repetition rate would be needed to track foraging by individual fish. The vertical resolutions of these sensors are *ca.* 12.5 cm. By employing two-way telemetry we were able to adapt our temporal sampling rates to quickly respond to the observed acoustic scattering patterns. When we needed very high-resolution data rates in order to avoid aliasing we used sampling intervals as short as 30 sec. During most of the deployment period we sampled at one-minute intervals. This was necessary to prevent spatial and temporal aliasing. The water column structure changed relatively rapidly at this study site, driven by both horizontal advection and modulation of vertical structures by internal waves. Telemetry connected the acoustic sensors and our shore station in Aptos. This allowed us to receive, archive, process and distribute the data very quickly. When sampling was being undertaken near the location of one of our TAPS-6 sensors, we normally used a 30 sec sampling rate, communicating a layer's depth, thickness, rates of rising or sinking, and other relevant environmental descriptors to a sampling team on a ship by radio.

WORK COMPLETED

The data acquisition phase of this project was successfully completed on 31 July 2006. We also served as the small boat coordinator for the LOCO program in both 2005 and

2006, and the gear deployed by our three boats was all successfully recovered. The data collected by BAE Systems personnel were archived and transferred to the University of Rhode Island for use in the data analysis and synthesis tasks to follow, as well as for use in preparing presentations and manuscripts for publication.

RESULTS

Our TAPS-6 sensors began measuring multi-frequency volume scattering strength data at 1800 PDT on July 11, 2006 (Fig. A1-2). The strongest scattering each day was just below the sea surface, and was correlated with increased winds during the early evening. Whether the scattering was due to bubbles injected by breaking waves, to mixing of zooplankton and bubble-bearing fish larvae into the water column, or to both, remains an open question. At the beginning of our deployment, a thin, weak, sound scattering layer was observed near the pycnocline. Volume scattering strengths in the thin layer averaged about -60 dB at 420 kHz. This thin layer was strongly modulated in depth by an internal wave field. The acoustical scattering layer was *ca.* 1 to 2 m thick. It appeared to be relatively diffuse in its thickness, but was comparable in overall character to layer structures we observed at the same location in 2002. A similar layer was intermittently observed for varying periods throughout the period from July 11 through the end of our work at this station on July 29.

The thin scattering layer illustrated in Fig. A1-2 was usually seen in mid-water, but occasionally disappeared from view below the depth of the TAPS transducer face, nominally *ca.* 1.5 m above the seabed. This layer also occasionally appeared to approach the sea surface, disappearing from view within a few tens of cm of the air-water interface. Sometimes thin, the scattering layer occasionally dispersed vertically, often filling most of the water column.

Most of the biomass in the water column was best fit by a fluid sphere model (i.e., small copepods) with lengths < *ca.* 1 mm. However, the elongate scatterers in, and above the acoustical scattering layer were distinctly different in size. Above the layer, elongate organisms were 8 mm long. Within the scattering layer, i.e, between 6 m and 8 m above the TAPS, the organisms were 10 mm long (Fig. A1-3).

Two days into the LOCO 2007 experiment, the character of high frequency acoustic scattering in the water column changed to one dominated by patterns of reverse vertical migration (Fig. A1-4). Normal vertical migration patterns involve a diel behavior rhythm, with organisms swimming toward the sea surface at sunset and returning to their normal daytime habitat in deeper water at sunrise. The reverse vertical migration we observed has been previously described for zooplankton elsewhere (e.g., *Psuedocalanus spp.*, Ohman *et al.* 1983), although the present acoustic records provide more detail.

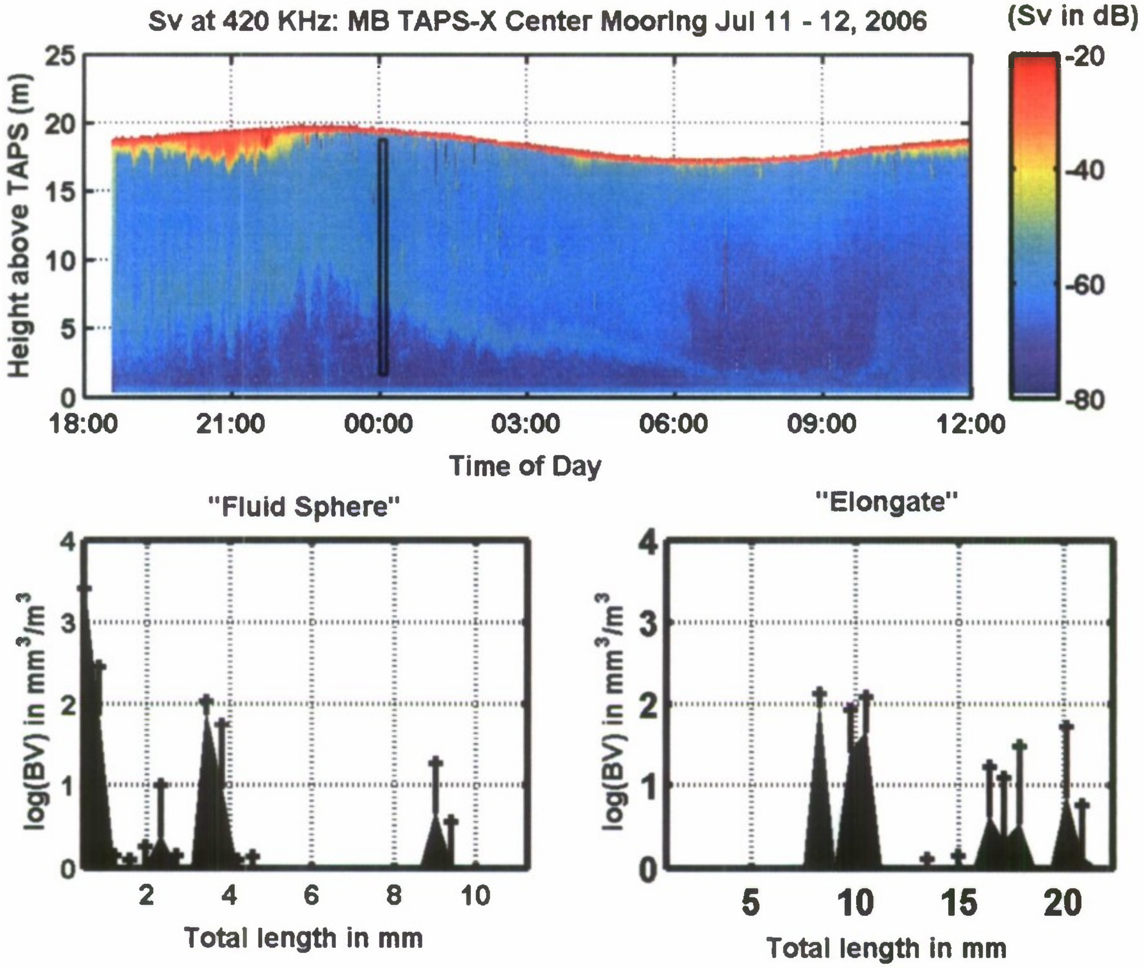

Figure A1-2: A TAPS-6 420 kHz record of volume scattering strength vs depth between 1800 PDT on July 11 and noon on July 12 revealed the presence of a thin scattering layer (top panel). The layer appeared to be modulated by internal waves and varied in depth over much of the 20 m deep water column. An inverse calculation for a small time interval and range of depths (see black box in top panel at midnight) showed that several sizes of scatterers were present for the two plankton shapes modeled (bottom left and bottom right panels). The first shape was a "fluid sphere" that was used to simulate scattering from small mesozooplankton such as fish and copepod eggs, small copepods, ostracods, etc. Organisms that scattered sound in a manner similar to "fluid spheres" were present at several sizes, the most abundant was for diameters of 0.25 – 0.75 mm. When summed over size, the mean biovolume in the box outlined in the top panel was 3,191 mm^3/m^3. A scattering model for elongate scatterers such as krill or mysids was also used in the inverse calculations, revealing even lower abundances of scatterers with elongate shapes. The average biovolume of elongate scatterers in the outlined box was only 173 mm^3/m^3. The lengths of the elongate scatterers present were 8, 10, 17, and 20 mm.

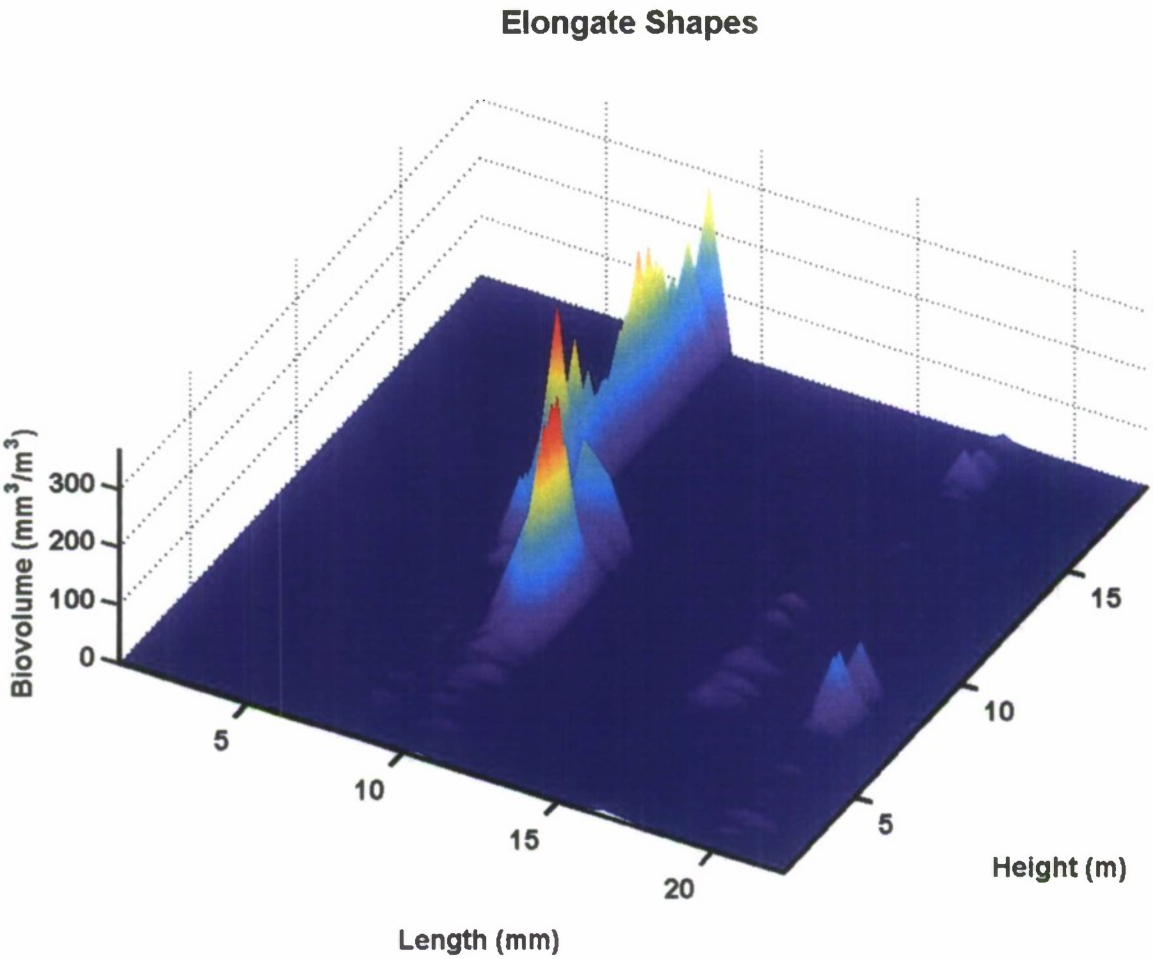

Figure A1-3: The inverse calculation for the box delineated in the top panel of Fig. A1-2 reveals a distinct difference in the sizes of the elongate scatterers above and within the acoustical scattering layer. In this figure, at the depth of the scattering layer for 420 kHz at midnight on July 11-12, most of the biovolume for the elongate scatters was found to be in the 10 mm size bin. Although there was a minor overlap in depth, most of the biovolume contributed by the elongate scatterers above the 420 kHz scattering layer was from organisms only 8 mm in length. The acoustical layer also received minor contributions from elongate scatterers that were ca. 17 and 21 mm in length.

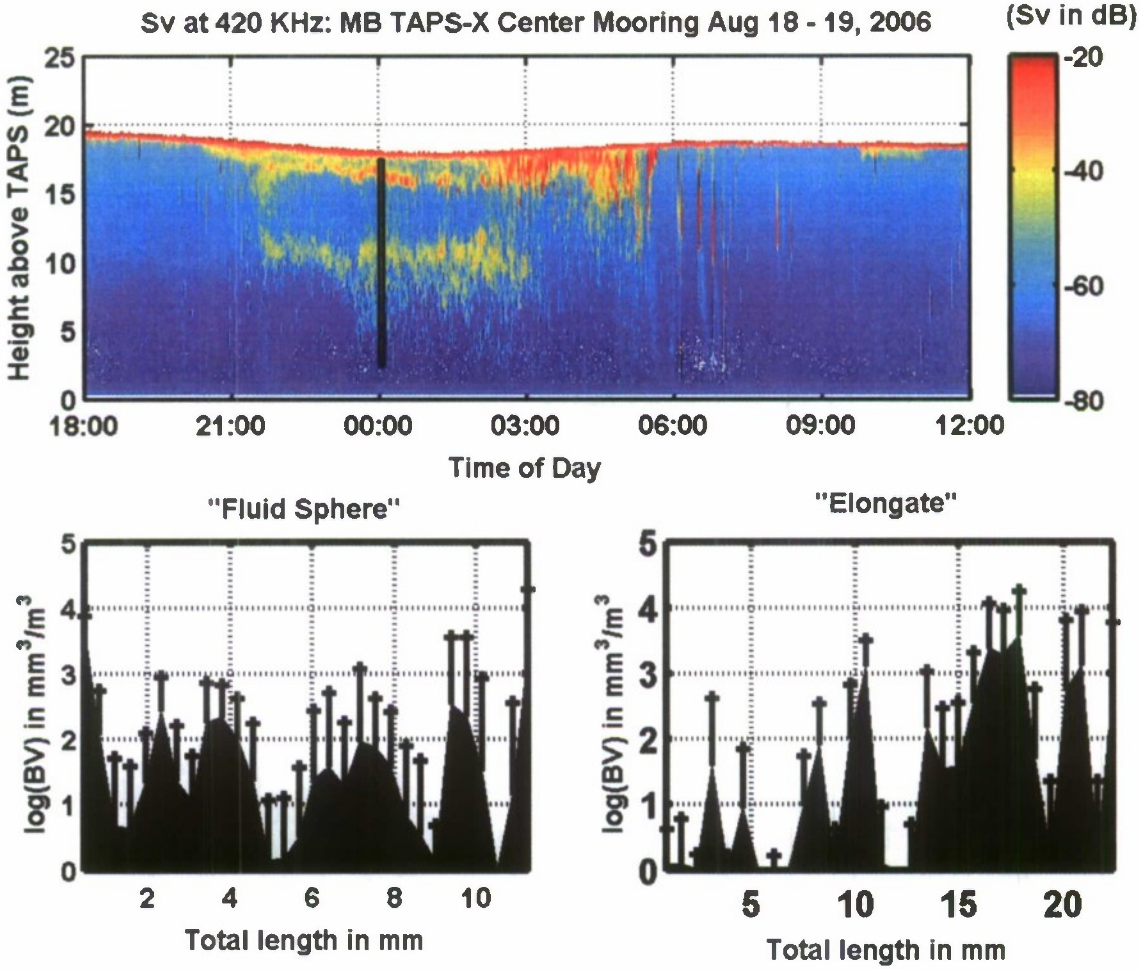

Figure A1-4: A TAPS-6 420 kHz record of volume scattering strength between the hours of 1800 PDT on July 18 and noon on July 19 revealed scattering layers that appeared just below the sea surface just before sunset (top panel). At sunset, the layers rapidly descended into the water column. One stopped at a depth of about 2 m, and the other continued downward until it reached about 9.5 m. Beginning at about 0300 PDT, the deeper layer gradually rose toward the surface, merging briefly with the upper layer before both rose to within a few tens of cm of the surface at ca. 0530 PDT. Small aggregations of scatterers, likely schools of small epipelagic fish, appeared to form between the surface and about 10 m depth between 0600 and 0800 PDT. In the bottom panels, an inverse calculation for a brief interval near midnight is displayed, and reveals the presence of numerous sizes of both elongate and quasi-spherical scatterers. Later in the month we were able to obtain qualitiative samples of the layer at 10 m with a net. The dominant zooplankter was Evade spp., but other copepods, e.g., Acarta tonsa, were present in low numbers. Although we captured only three mysids, our simple sampling methods would have allowed most micronekton to evade capture. Even so, the three specimens we did capture were of appropriate sizes to have explained the three peaks in biovolume between ca. 8-20 mm.

After July 12, the scattering was characteristic of a reverse migration in which most of the scattering organisms were located just under the surface during the day. At sunset, one or more layers would descend into the water column, where they would remain until between 0200 and 0500 PDT. During that interval the layers would gradually appear to diffuse and move towards the surface, usually arriving long before sunrise. When reverse vertical migration occurs, there is usually a presumption that the organisms are leaving the surface to forage, although the behavior also changes exposure to predation.

Six hour scattering records collected at the beginning and in the middle of July 2007 are provided to contrast periods during which the scattering in the water column was dominated by a thin layer structure (Fig. A1-2) and a time interval when reverse migration was present (Fig. A1-4). There were also days when both water column structures were seen simultaneously. Thin layer formation was not completely consistent during the periods when reverse migration occurred. Sometimes the upper half of the water column would simply be "filled" with downward migrators without the clear coalescing of distinct thin layers. The observed patterns were reminiscent of similar patterns observed in Aug / Sept at this site during 2005. Weak episodes of emergence and re-entry from and to the seabed were occasionally obseved (e.g., Abello *et al.* 2005), but there did not appear to be a strong correlation with either light or tides. A short net tow during the day revealed the presence of very small numbers of copepods within 0.5 m of the surface, tentatively identified as *Acartia tonsa.*

Data from other TAPS deployed in the area near the one for which the figures above were taken revealed patterns sufficiently similar to convince us that the temporal patterns of vertical distribution in this area were correlated over horizontal distances of at least 2 km, and that reverse vertical migration was the dominant process leading to zooplankton aggregation at particular depths. The observed acoustical backscattering was consistent with different proportions of small copepod-shaped and large elongate zooplankton in different layers. Most of the night-time zooplankton biomass originated from the surface waters, with much lower amounts episodically emigrating from the seabed. In contrast to 2002, during the same month, daytime thin zooplankton layers were largely absent or contained relatively little biomass. The layers that were present sometimes met the criteria for "thin layers" in Dekshenieks *et al.* 2001, but often they could be seen to gradually diffuse into the water column, technically not meeting the criteria for true "thin layers" for long periods before forming into another thin layer.

IMPACT/APPLICATIONS

Taken together, the data collected during 2002, 2005 and 2006 in Monterey Bay strongly suggest that fine-scale vertical structures and diel vertical migrations by the plankton are ecologically significant. As aggregating mechanisms they impact food availability for several trophic levels, but especially for larval organisms before they are able to swim in order to forage effectively. In 2007 we collected a time series that reveals changes in thin layer structures over several weeks. When these data are examined in the light of several data sets (e.g., phytoplankton and chl-a profiles, plankton species, small scale physical

oceanography, etc.) collected by our co-PIs in LOCO, numerous questions that cut across physical and biological forcing in the coastal ecosystem can be addressed. The LOCO data are truly unique, with several components resulting from sampling that was specifically directed to observed phenomena as a result of having real-time data from the TAPS and ORCAS variants deployed by the BAE Systems and URI teams. The distribution of marine life at all trophic levels impacts current and future naval systems, especially those used in shallow water, where both mine detection and clearing operations must be conducted prior to engaging in expeditionary warfare. The abundance and distribution of marine life also plays an as yet poorly understood role in controlling reverberation statistics at lower acoustic frequencies through food web interactions.

TRANSITIONS

Some of the multi-frequency technology we developed under sponsorship of ONR has been transitioned to operation in the North Pacific and Bering Sea areas by NOAA's National Marine Fisheries Service / Alaska Fishery Science Center and the Pacific Marine Environmental Laboratory (PMEL). An 8-frequency sensor is currently moored in the Bering Sea, where it has been measuring volume scattering data via the Iridium system every 20 minutes from a depth of 17 m, and reporting it to PIs ashore hourly since late-April, 2007. This mooring will be retrieved in late September before the ice covers the shelf area. The acoustical volume scattering strength data are being processed to estimate abundances of zooplankton and micronekton for use in trophic models for the area. This system was moored from mid-April until the end of September in the same location in 2006. The Bering Sea supports one of the most economically valuable fisheries in the US EEZ. Estimates are that between 40 and 50% of the fish consumed in the US come from fisheries in that ocean area. The present deployment follows multi-month deployments on moorings by NOAA in the Coastal Gulf of Alaska in 2002, '03 and '04. Those data revealed continuing declines in North Pacific zooplankton biomass (Napp, et al. 2004; Holliday et al. 2005a; Holliday et al. 2005b; Bond et al. 2006).

RELATED PROJECTS

We consulted with NOAA and PMEL personnel in support of the transition discussed above. This consulting effort was funded under NOAA Contract AB133F05SU3288.

REFERENCES

Abello, H.U., S.M. Shellito, L.H. Taylor, and P.A. Jumars. 2005. Light-cued emergence and re-entry events in a strongly tidal estuary. Estuaries 28(4): 487-499.

Bond, Nicholas A., D.V. Holliday, Calvin W. Mordy, Jeffrey M. Napp and Phyllis J. Stabeno. 2006. Linkages between physical conditions in the coastal Gulf of Alaska and zooplankton biomass and size composition during 2002-04. PICES/GLOBEC Symposium (Poster T2-2684).

Dekshenieks, Margaret M., Percy L. Donaghay, James M. Sullivan, Jan E. B. Rines, Thomas R. Osborn, and Michael S. Twardowski. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. Marine Ecology Progress Series 223: 61–71.

Holliday, D.V. 1977. Extracting Bio-Physical Information from the Acoustic Signatures of Marine Organisms. In Ocean Sound Scattering Prediction, N.R. Anderson and B.J. Zahuranec, Eds. Marine Science Series Vol. 5, Plenum Press, New York, NY, pp. 619 - 624.

Holliday, D.V. and R.E. Pieper. 1980. Volume scattering strengths and zooplankton distributions at acoustic frequencies between 0.5 and 3 MHz. J. Acoust. Soc. Am. 67: 135-146.

Holliday, D.V., J.M. Napp, C.F. Greenlaw and P.J. Stabeno. 2005a. Interannual comparisons of zooplankton biomass in the Gulf of Alaska using bioacoustical sensors. PICES (Poster)

Holliday, D.V., J.M. Napp, C.F. Greenlaw and P.J. Stabeno. 2005b. Intra- and inter-annual comparisons of zooplankton biomass in the Gulf of Alaska using bioacoustical sensors. J. Acoust. Soc. Am. 118(3): 1908. (A).

Napp, J.M., C.F. Greenlaw, D.V. Holliday and P.J. Stabeno. 2004. Advection of shelf zooplankton in a predominantly down-welling ecosystem: Bioacoustic Detection of the dominant modes of variability. (PICES Poster)

Ohman, M.D., B.W. Frost, and E.B. Cohen. 1983. Reverse diel vertical migration: An escape from invertebrate predators. Science 220 (4604): 1404-1406.

PUBLICATIONS

Anderson, John, Van Holliday, Rudy Kloser, Dave Reid and Yvan Simard (Eds.). 2007. *Acoustic Seabed Classification of Marine Physical and Biological Landscapes*. ICES Cooperative Research Report, Rapport des Recherches Collectives, No. 286. 183 pp. [refereed].

Anderson. John T., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard. 2007. Chapter 10: Future directions for acoustic seabed classification science. In *Acoustic Seabed Classification of Marine Physical and Biological Landscapes*. John T. Anderson, Ed., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp.139-146. [refereed].

Anderson, J.T., D. V. Holliday, R. Kloser, D. Reid, and Y. Simard. Acoustic Seabed Classification: Current Practice and Future Directions. ICES Journal of Marine Sciences. [submitted, refereed].

Cheriton, Olivia M., Margaret A. McManus, D.V. Holliday, Charles F. Greenlaw, Percy L. Donaghay, and Tim Cowles. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the west coast of the U.S. Estuaries & Coasts [in press, refereed].

Holliday, D.V. 2007. Chapter 2: Theory of sound scattering from the seabed. In *Acoustic Seabed Classification of Marine Physical and Biological Landscapes*. John T. Anderson, Ed., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp. 7-28. [refereed].

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. In *The American Institute of Fisheries Research Biologists' 50th Anniversary Proceedings*, Richard Beamish and Brian Rothschild (Eds). [submitted, referred].

Appendix A2: Annual Progress Report for 2007 (Phase II)

Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis - II

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LONG-TERM GOALS

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at the scales that control how they live, reproduce, and die.

OBJECTIVES

Working with researchers from several institutions, we have been studying layered organization in the coastal ocean (LOCO) with an emphasis on describing thin layers of zooplankton in relation to their small-scale vertical environments. We have two major near-term objectives. First, we are comparing our data from two experiments in Monterey Bay with those of our collegues in the LOCO program and preparing several publications. During the last half of FY 2007 we focused on the analysis of data collected during FY 2005 and 2006. Additional data from a brief occupation of the same coastal site during 2002 are also being used to support our analysis effort. Our second objective supports the first, and involves making several major upgrades to our custom data analysis software. One of these upgrades has been to add a capability to extract information from our acoustical measurements about the distribution and sizes of very small gas bubbles (1 to 50 microns radius) in the water column.

Graduate School of Oceanography
The University of Rhode Island

APPROACH

Both of the investigators listed above retired from BAE Systems during the first half of FY 2007. They have been active in the LOCO program since its inception. Under a grant to the University of Rhode Island (URI) they are continuing to work up the LOCO data that they have collected. The data acquisition for LOCO was carried out during the period from October 2006 through Feburary 2007 and is summarized in a companion report. Progress on the analysis of the LOCO data during the period from April 2007 through the end of FY 2007 is the subject of this report.

During the late summer and early fall of 2005 and 2006, very thin layers of phytoplankton, zooplankton, nutrients, and water column physical structure were studied by a part of the LOCO research team at several closely spaced shallow, near-shore stations in northeastern Monterey Bay. Other team members examined larger scale horizontal distributions and temporal thin layer patterns in deeper water nearby, while still others collected plankton and made measurements of turbulence and various optical properties of the water column. Our part of this research involved the deployment of several acoustic and ancillary sensors on the seabed. The acoustic sensors were used to describe the distributions of small zooplankton, micronekton and small gas bubbles.

The data acquisition phase of LOCO was successfully completed on 31 July 2006. We are now approximately at the 20% point in the two-year analysis and synthesis phase. We are organizing specific data sets to support papers that we, and our colleagues, are preparing, adding new capabilities to some of the software we use to process and display our acoustical volume scattering data, and examining data sets from several ancillary sensors that we used during the 2006 field-work.

WORK COMPLETED

To date, we have plotted and examined all of the acoustical volume scattering strength profiles from the field work in Monterey Bay from both 2005 and 2006. These data are available to any LOCO principal investigator and their team members. Preliminary results can be accessed by team members at the U of HI's LOCO project web site. An ongoing part of our analysis work also involves responding to specific requests for data or information by any of our LOCO co-PIs. We have answered several of these requests, and anticipate many more as the analysis proceeds.

We have been upgrading several of our custom software analysis packages. One improvement involved adding new capabilities to our inverse code. The basic principles behind these calculations can be found in Holliday (1977) and in Holliday *et al.* (2003a). We use these programs to process volume scattering strength (Sv) measurements collected with our acoustical sensors. The acoustical spectra are used to make estimates of the size-abundance spectra at different depths and times. In the past these data processing codes were limited to making estimates for organisms with any two of three basic scattering

types. One of these is an acoustically penetrable fluid sphere. It is used to model acoustic scattering from small zooplankton. Many common small copepods, their eggs, and fish eggs approximate this shape and scatterer type. Another scattering model we use is the rigid sphere. It has been used to approximate scattering from organisms such as shelled pteropods and has also been used when sand was in the water column, although better approximations may now be available and are being considered for inclusion in our analysis code. The third model we have used is for elongate micronekton, such as krill or mysids. Given a scaled outline, scattering from organisms with elongate shapes can be modeled in 2-D by using a distorted wave Born approximation. We have models for several species of elongate copepods, krill, and mysids. We have recently added the capability of modeling very small gas bubbles. Our inverse code now simultaneously calculates size-abundance spectra for particles represented by any two of these types of scatterers, plus small bubbles.

RESULTS

Multiple frequency TAPS zooplankton acoustics sensors were deployed at the LOCO site K1 on the shelf just SW of Aptos, CA (see Fig. A1-1 in Appendix A1). These sensors "look" upward into the water column much like an inverted echo sounder. Described in detail elsewhere (Holliday 2003a), narrow beams at frequencies of 265, 420, 700, 1100, 1850 and 3000 kHz are used to measure volume scattering strengths throughout the water column. The vertical resolution is 12.5 cm. Sixteen echo ranging cycles are are collected at programmable intervals of as short as 30 sec. An interval of 1 min was used for the data in this report. Two way telemetry between the TAPS and a shore station in Aptos, CA allowed us to display and distribute data from these sensors quickly. The systems were also controlled from shore in an adaptive manner during the LOCO research field period. In order to minimize aliasing, faster sampling was used when the observed scattering was changing rapidly. We also used this capability to slow the sampling and save battery power when fast sampling was deemed less critical. A representative multi-day sample of data from our TAPS-6 sensors illustrates the variability in acoustical scattering (Figs. A2-1 and A2-2).

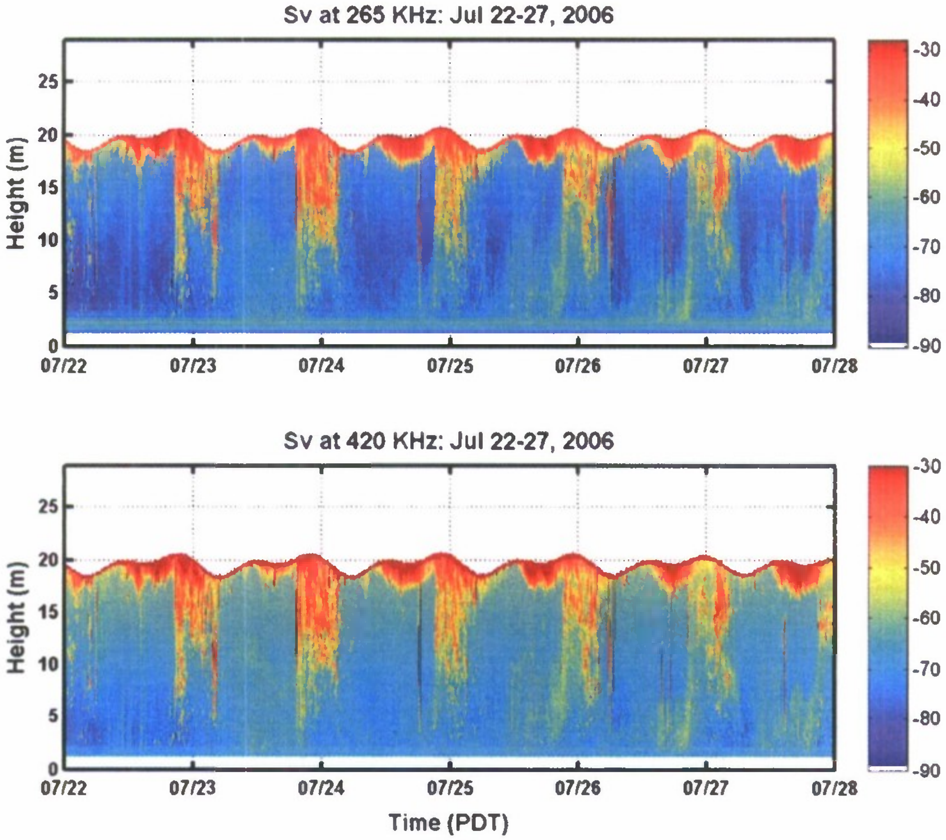

Figure A2-1: Volume scattering strength profiles from a TAPS-6 acoustical zooplankton sensor at a location on the shelf near Aptos, CA revealed the presence of variability of ca. 60 dB, or a difference of one million in sound scattering intensity from depth-to-depth and time-to-time in the 20 m water column. The 6 day record reveals strong diel variability at 265 kHz (top panel) and 420 kHz (bottom panel), with the night-time scattering generally being higher in the top half of the water column.

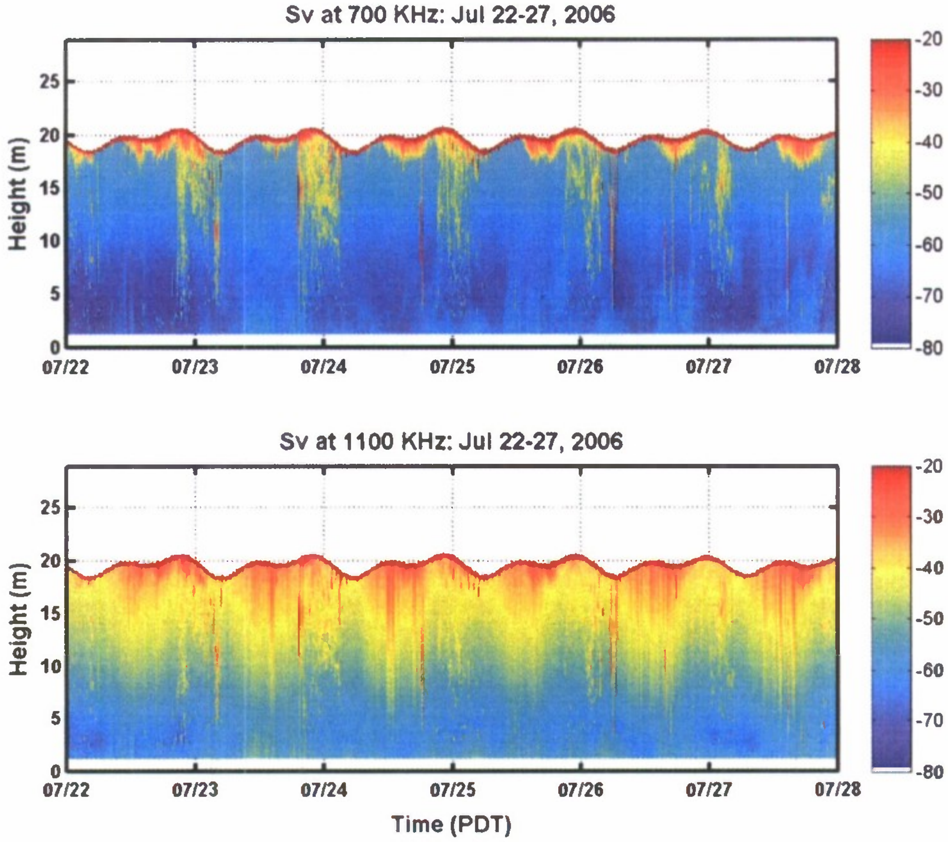

Figure A2-2: The volume scattering strength profiles at 700 and 1100 kHz (top and bottom panels respectively) also reveals the presence of variability of ca. 60 dB during the same period displayed in Fig. A2-1. (Note the change in the color scale). The day-time scattering was also generally higher at 1100 kHz and at higher frequencies (not shown here), with "plumes" of high scattering extending from the surface well into the water column (bottom panel). Episodic "emergence" events can also be seen originating near, in or on the sea floor.

Water temperature was measured with internally recording thermisters at 1 m depth intervals on the vertical mooring cable below the nearby spar buoy used to support the TAPS telemetry. The water temperature was also measured by the TAPS at *ca.* 30 cm above the seabed. These measurements were combined to reveal variability in the water termperature through the entire water column at the site (Fig. A2-3). The downwelling light at a sensor on the TAPS, *ca.* 1 m above the seabed also provided information regarding variations in downwelling irradiance.

Focusing on the 265 kHz record (Fig. A2-1, top panel), we can see evidence of the vertical movement of sound scattering organisms over relatively short periods. Some traces appear to indicate that the organisms are swimming down (negative slope in time-depth), while at other times, there is an upward trending trace with advancing time. Examples of the former include six downward migration events between noon and 18:00

PDT on 7/21 and strong downward morning migrations from the water column to a location near the seabed. Upward migrations can be seen at each sunset , starting near the seabed and often appearing to reach the surface. When plotting these scattering data in a space of 1.4" x 1.375" independent pixels overlap, sometimes suppressing critical evidence of fine structure.

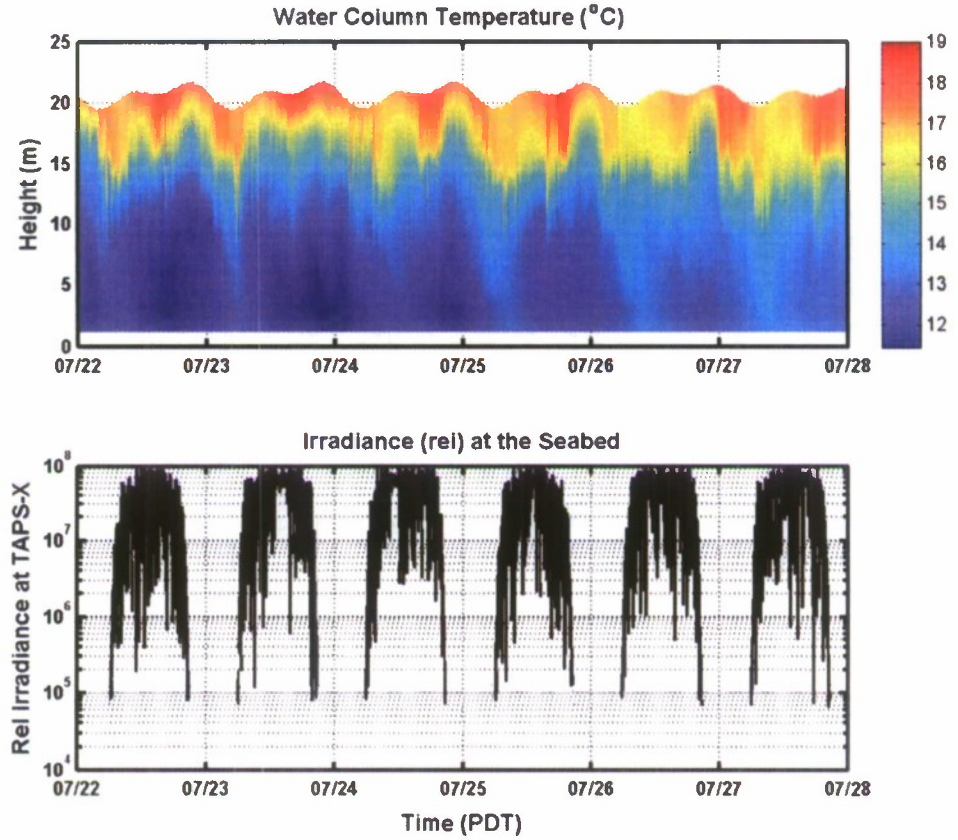

Figure A2-3: The water column temperature profile (top panel) reveals variations throughout the water column. A weak thermocline persisted at depths of less than 1 m to ca. 5 m (14 to 15 m height above the seabed), but plumes or intrusions of warmer water penetrated to various depths, including to the seabed during the later part of the 6 day period illustrated. Relative irradiance at the seabed varied during the daytime hours, but peak levels near solar noon were remarkably constant (bottom panel).

If one relies strictly on the images presented in Figs. A2-1 through A2-3, the dominant pattern appears to be a simple migration from the seafloor to the surface at sunset each night, and back to the bottom beginning before sunrise. The profiles in Figs. A2-1 and A2-2 each contain 8,641 independent scattering profiles, each with 220 depth intervals. Overplotting of pixels masks the fine detail. While an overview is essential, it is useful to expand the scales. An expanded version of the data from 1800 July 26 through 0600 July 27 reveals a complex overall pattern (Fig. A2-4, top panel). A close examination of the profiles reveals patterns that differ from frequency-to-frequency, an anticipated result

that can be traced to the non-linear, non-monotonic scattering from the zooplankton at these frequencies. There are also large differences with time and depth at single frequencies. At the expanded scale (Fig. A2-4) there is clear evidence of a migrating diffuse layer. This layer was associated with the bottom during the day, rose into the water column at night, and returning to a deeper location before sunrise. This layer was more distinct, slowly meandering in depth for a few days early in our occupation of this site (e.g., July 11 and 12). Similar patterns were observed in 2002 and 2005. In terms of biovolume, an analog of displacement volume and biomass, the organisms in this diffuse layer were dominated by copepod-like scatterers with lengths of < 1 mm with biovolumes of *ca.* 1000 mm^3/m^3. Copepods with lengths of *ca.* 1 mm were also present at biovolumes of 100 mm^3/m^3 in this layer. Elongate scatterers with lengths of 3 and 6 mm were present as well, with biovolumes of 10 mm^3/m^3 at each of these two sizes. Gas bubbles (< 3 microns radius) were detected near the seafloor in abundances of between 10^5 and 10^6 / m^3. Bubbles with radii of 8 and 12 microns were present in abundances of < 100 / m^2. The smaller of these two bubble groups disappeared after rising about 3 m into the water column, and the larger bubbles declined to near zero abundance at *ca.* 9 m above the seabed. The sizes in both of the larger bubble groups increased slightly as they rose in the water column. On the night of July 26-27, organisms that had been near the seafloor filled the water column, eventually returning to a location near, but slightly above the seafloor, beginning their descent well before sunrise (*ca.* 0300 PDT). First light was *ca.* 0600 PDT.

About 2230, a thin scattering layer formed at a depth of *ca.* 2.5 m. If, for zooplankton, one adapts the criteria for a thin layer as formulated for phytoplankton (Dekshenieks *et al.* 2001), on that particular night this layer barely qualified as a "thin" layer. Its location suggests that the organisms in the layer were attempting to maintain an association with a weak thermocline (Fig. A2-4, bottom panel) or with some other characteristic of the water that was present near the thermocline. The pattern is consistent with a temporally coherent vertical migration of a thin layer that was horizontally discontinuous, or patchy. These observations were also consistent with night time shipboard echo sounder records.

Possibly as the result of horizontal advection, a plankton patch was observed in the upper mixed layer, beginning at about 0130 PDT. When observed at higher resolutions both the layer and the patch can be seen to contain discrete scatterers with target strengths and spectra consistent with those of fish. The patch itself contained scatterers that exhibited the spectral scattering characteristics of copepods or fish eggs < 1 mm in size with a total biovolume of *ca.* 10,000 mm^3/m^3. This is the equivalent of a cube of plankton that measures 2.15 cm on each side. Two additional sizes of organisms were also present, with lengths of 2 and 3 mm. Biovolumes in these two size classes were *ca.* 1,000 and 100 mm^3/m^3 respectively. Elongate scatterers, 10.5 mm in length were also present at a biovolume of 6,300 mm^3/m^3. Bubble sizes and abundances were similar to those detected elsewhere in the water column.

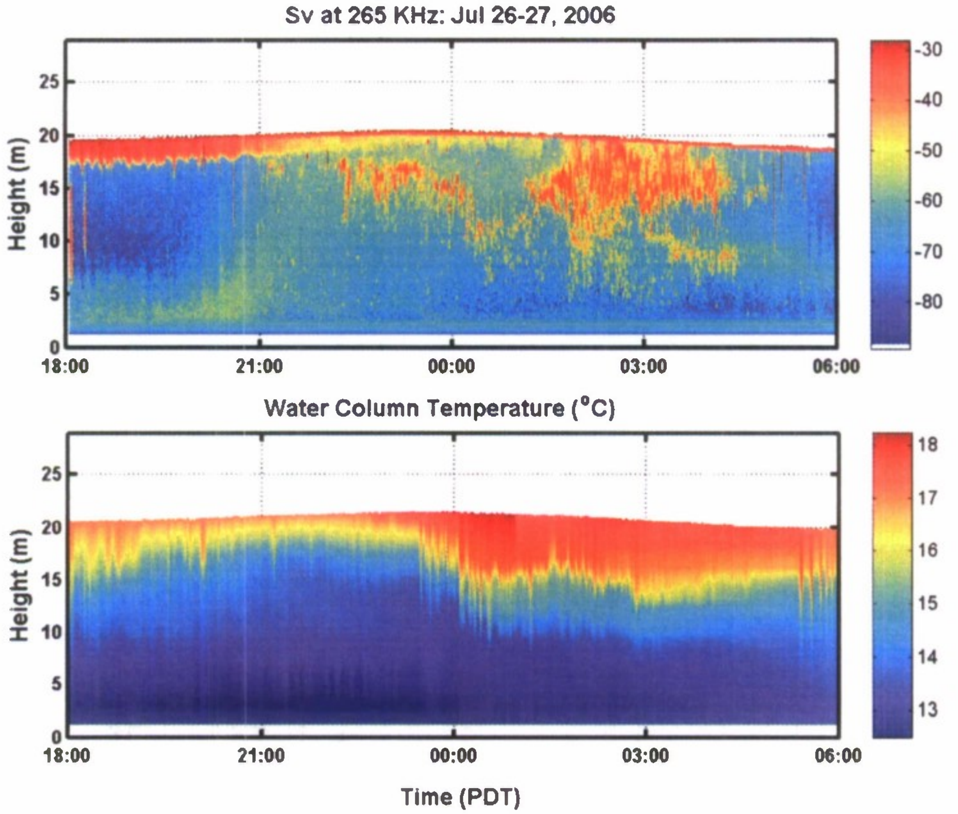

Figure A2-4: Acoustical volume scattering at 265 kHz for 12 hours centered on midnight at LOCO site K1 revealed both a normally migrating diffuse layer dominated by scatterers with Sv spectra typical of small copepods (top panel). The rise of this layer from near the seabed was synchronized with sunset. A second layer with the acoustic spectral characteristics of a mix of copepods and elongate scatterers with body shapes similar to that of mysids or euphausiids descended from the surface into a weak thermocline. The thermocline deepened near slack water and its depth continued downward as the tide receeded (bottom panel). The thin layer roughly followed the depth of the thermocline. The deepening upper mixed layer contained a patch that was a mix of zooplankton and micronekton. Observations at a higher spatio-temporal resolution revealed the presence of high target strength scatterers, e.g., small pelagic fish, with in both the thin layer and the patch.

Schools of small pelagic fish (e.g., just after 1800 PDT) were observed visually during the day from LOCO support ships, including the R/V Thompson. From the inshore TAPS records, it appears that the schools dispersed at night, re-forming the next morning when there was sufficient light for schooling. The volume scattering strength spectra in the migrating diffuse scattering layer, the thin layer, and the patch were consistent with low

abundances of fluid sphere and elongate scatterers that are used as surrogate scattering models for small zooplankton (e.g., copepods) and micronekton (e.g., mysids). On days not included in this discussion, the patterns shown in Figs. A2-1 through A2-3 were fairly typical of those illustrated. Taken as a whole, the data strongly suggest that a night time thin layer originated just under the sea surface at sunset, with the organisms performing a reverse migration into the water column, sometimes splitting into coherent thin layers at multiple depths. Reverse migrations are fairly common in the zooplankton community, as are normal vertical migrations where organisms move into the water colum at night, returning to a place they perceive as relatively safe during the day. This can be near the seabed (Kringel *et al.* 2003) or near the surface (Ohman *et al.* 1983). The migrations we observed appear to be behavior-driven, and in the light of data our co-PIs collected in Monterey Bay they are probably related to foraging. In 2006, the Monterey Bay thin layers consistently started a return to the surface at *ca.* 0300 PDT, arriving there in multiple cohorts well before sunrise. This layer contained organisms that scatter sound with a frequency dependence similar to that observed for copepods and other small, quasi-spherical particles, e.g., fish and copepod eggs. Biovolumes for organisms with lengths < 1 mm were about 40X greater in the thin layer originating at the surface than in the diffuse layer that rose from the bottom, i.e., *ca.* 40,000 mm^3/m^3. Organisms that scattered sound like 12 mm krill were present in the 1 m thick thin layer at similar abundances, with less biomass above and below the layer. The number of bubbles with radii < 4 microns reached values of *ca.* 63 M / m^3, higher than was measured just under the sea surface at the same time. Bubbles with radii of 8.5 microns were also present. Their numbers reached *ca.* 10,000 / m^3 within the layer, dropping to near zero just above and below the layer. Fourteen micron radius bubbles appeared to be passing through the layer, with fewer bubbles both below and above the layer peak. The bubble density was assymetric, higher below the layer than above, suggesting possible accumulation of rising bubbles at the thin layer depth. This was also the case for the bubbles < 4 micron in radius. Our estimates of bubble sizes and numbers in the water columm are consistent with acoustical resonator measurements from Monterey Bay (Medwin 1977). Medwin and Breitz (1989) used optics to find that the peak in the size spectrum for subsurface bubbles was < 30 microns. While much of our data remains to be analyzed, our initial results seem consistent with their results and those of Wu (1981). Multiple physical mechanisms have been identified to explain the distribution of small bubbles in the sea (Monahan and Lu 1990). Considerable literature exists on small bubbles in the sea, and our plans include additional comparisons of our measurements with results obtained by other investigators, including Medwin, Farmer, Crawford, Vagle, Su, Thorpe, Leighton and Humphries. Most studies on bubbles in the sea have emphasized physical processes such as breaking waves, stimulated by an interest in air-sea interactions and ocean-atmosphere gas exchange. Our primary focus involves the possibility that small bubbles may be generated as a result of disolved O_2 saturation as a result of photosynthesis where phytoplankton concentrate in very thin, shallow layers in the water column. We have shown that such bubbles may be produced by epi- or endo-benthic marine algae in the top few mm of a sandy seabed (Holliday *et al.* 2003b; Holliday *et al.* 2004). In addition to *in situ* generation, a seabed source of bubbles in a shallow, sandy area such as the shelf of Monterey Bay could be an added, or alternate, explanation for the presence of small

bubbles in thin layers. A flux of small bubbles rising slowly upward could possibly be delayed or trapped at depths with high concentrations of marine snow or mucous derived from living organisms, or within dense thin layers of phytoplankton.

IMPACT/APPLICATIONS

The data collected in the LOCO work in Monterey Bay during 2002, 2005 and 2006 strongly suggest that fine-scale vertical structures in the plankton and their diel vertical migrations are ecologically important. As aggregating mechanisms they impact food availability for several trophic levels and they are critical for larval organisms before they are able to swim and forage effectively. When our data are examined in the light of the different data sets (e.g., phytoplankton and chl-a profiles, plankton species, small scale physical oceanography, etc.) collected by our co-PIs in LOCO, we will be able to address questions involving physical and biological forcing in the coastal ecosystem. The LOCO data sets are truly unique. Having access in real-time to data from the TAPS and ORCAS variants deployed by the BAE Systems and URI teams has proven extremely valuable, allowing the investigators to adapt their sampling efforts in a way that assured that the same fine-scale phenomena were actually sampled by a large suite of appropriate sensors. The distribution of marine life at all trophic levels impacts current and future naval systems, especially those used in the littoral (coastal) zone, where both mine detection and clearing operations must be conducted prior to engaging in expeditionary warfare. The abundance and distribution of marine life also plays an as yet poorly understood role in controlling reverberation statistics at lower acoustic frequencies through food web interactions. The phenomena we have studied impacts the propagation and scattering of both light and sound. Information gained will be invaluable for designers of new sensors to be used in the battlespace environment.

TRANSITIONS

Some of the multi-frequency technology that we developed under sponsorship of ONR has been transitioned to operation in the North Pacific and Bering Sea areas by NOAA's National Marine Fisheries Service / Alaska Fishery Science Center and the Pacific Marine Environmental Laboratory (PMEL). We will be adding the new capabilities in our inverse code to the custom software that is used to process the data NOAA is currently collecting in the Bering Sea with a moored 8-frequency TAPS. This will also provide a capability for extracting the densities of small bubbles from TAP-8 archival data collected in the Coastal Gulf of Alaska in 2003, 2004, and 2005 and in the Bering Sea during 2006.

RELATED PROJECTS

We continue to support NOAA and PMEL personnel regarding TAPS-8 data processing. This project is funded by NOAA/COP through NOAA's Alaska Fisheries Science Center. Several posters and talks have been prepared and presented (Bond et al. 2006; Holliday et al. 2005b; Napp et al. 2004). We have also prepared and submitted a paper for publication in Deep Sea Research on the data they collected in the coastal Gulf of Alaska, and we are organizing at least one additional paper about those data. Our co-PIs

at NOAA have now collected two years of data from the Bering Sea shelf area north of the Aleutian Islands. We will be assisting NOAA in the processing and publication of papers related to the collection of those data, which are now transmitted hourly to shore via the Iridium satellite network.

REFERENCES

Bond, Nicholas A., D.V. Holliday, Calvin W. Mordy, Jeffrey M. Napp and Phyllis J. Stabeno. 2006. Linkages between physical conditions in the coastal Gulf of Alaska and zooplankton biomass and size composition during 2002-04. PICES/GLOBEC Symposium (Poster T2-2684).

Dekshenieks, Margaret M., Percy L. Donaghay, James M. Sullivan, Jan E. B. Rines, Thomas R. Osborn, and Michael S. Twardowski. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. Marine Ecology Progress Series 223: 61–71.

Holliday, D.V. 1977. Extracting Bio-Physical Information from the Acoustic Signatures of Marine Organisms. In Ocean Sound Scattering Prediction, N.R. Anderson and B.J. Zahuranec, Eds. Marine Science Series Vol. 5, Plenum Press, New York, NY, pp. 619 - 624.

Holliday, D.V., J.M. Napp, C.F. Greenlaw and P.J. Stabeno. 2005a. Interannual comparisons of zooplankton biomass in the Gulf of Alaska using bioacoustical sensors. PICES (Poster)

Holliday, D.V., J.M. Napp, C.F. Greenlaw and P.J. Stabeno. 2005b. Intra- and inter-annual comparisons of zooplankton biomass in the Gulf of Alaska using bioacoustical sensors. J. Acoust. Soc. Am. 118(3): 1908. (A).

Holliday, Dale V., Percy L. Donaghay, Charles F. Greenlaw, Duncan E. McGehee, Margaret M. McManus, Jim M. Sullivan and Jennifer L. Miksis. 2003a. Advances in defining fine- and micro-scale pattern in marine plankton. Aquatic Living Resources 16(3): 131-136.

Holliday, D.V., C. F. Greenlaw, D. Thistle and J.E.B. Rines. 2003b. A biological source of bubbles in sandy marine sediments. J. Acoust. Soc. Am. 114(4): 2314 (A).

Holliday, D.V., Charles F. Greenlaw, Jan E.B. Rines and David Thistle. 2004. Diel variations in acoustical scattering from a sandy seabed. Proceedings of the ICES 2004 Annual Science Conference, Vigo, Spain. International Council for the Exploration of the Sea, Copenhagen, Denmark. ICES CM 2004 / Session T (A).

Medwin, H. 1977. In situ acoustic measurements of microbubbles at sea. J. Geophys. Res. 82(6), 971–976.

Medwin, H. and N.D. Breitz. 1989. Ambient and transient bubble spectral densities in quiescent seas and under spilling breakers. J. Geophys. Res. 94: 12751-12759.

Monahan, E.C. and M. Lu. 1990. Acoustically relevant bubble assemblages and their dependence on meteorological parameters. IEEE J. Ocean Eng. 15: 340-345.

Napp, J.M., C.F. Greenlaw, D.V. Holliday and P.J. Stabeno. 2004. Advection of shelf zooplankton in a predominantly down-welling ecosystem: Bioacoustic detection of the dominant modes of variability. (PICES Poster)

Ohman, M.D., B.W. Frost, and E.B. Cohen. 1983. Reverse diel vertical migration: An escape from invertebrate predators. Science 220 (4604): 1404-1406.

Wu, J. 1981. Bubble populations and spectra in near-surface ocean: summary and review of field measurements. J. Geophys. Res. 86: 457-463.

PUBLICATIONS

Anderson, John, Van Holliday, Rudy Kloser, Dave Reid and Yvan Simard (Eds.). 2007. *Acoustic Seabed Classification of Marine Physical and Biological Landscapes*. ICES Cooperative Research Report, Rapport des Recherches Collectives, No. 286. 183 pp. [referred].

Cheriton, Olivia M., Margaret A. McManus, D.V. Holliday, Charles F. Greenlaw, Percy L. Donaghay, and Tim Cowles. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the west coast of the U.S. Estuaries & Coasts [in press, refereed].

Holliday, D.V. 2007. Chapter 2: Theory of sound scattering from the seabed. In *Acoustic Seabed Classification of Marine Physical and Biological Landscapes*. John T. Anderson, Ed., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp. 7-28. [refereed].

Anderson. John T., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard. 2007. Chapter 10: Future directions for acoustic seabed classification science. In *Acoustic Seabed Classification of Marine Physical and Biological Landscapes*. John T. Anderson, Ed., D. V. Holliday, Rudy Kloser, David Reid, and Yvan Simard, Assoc. Eds. International Council for the Exploration of the Sea, Copenhagen, Denmark, pp.139-146. [refereed].

Anderson, J.T., D. V. Holliday, R. Kloser, D. Reid, and Y. Simard. Acoustic Seabed Classification: Current Practice and Future Directions. ICES Journal of Marine Sciences. [submitted, refereed].

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. In *The American Institute of Fisheries Research Biologists' 50th Anniversary Proceedings*, Richard Beamish and Brian Rothschild (Eds). [submitted, referred].

HONORS/AWARDS/PRIZES

In 2006 NOAA named a new 32' coastal research vessel the R/V D.V. Holliday. This vessel can sleep up to four persons and is configured to operate up to 100 nm offshore. Instrumentation currently includes Simrad EK60 multi-frequency echosounders (38, 70, 120 and 200 kHz) and a Simrad SM20/SM2000 200 kHz multi-beam sonar. Additional scientific gear includes passive acoustic sensors, an ROV and an AUV, underwater video, a Seabird SBE19+ CTD, a WeatherPak 2000 weather station, an IKMT plankton net, and a NOAA shipboard computing system. Her homeport is in San Diego, CA, and the vessel is currently used for advanced research in fisheries and plankton acoustics, as well as for routine fisheries acoustic surveys along the US Pacific coast.

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Appendix B: Annual Progress Report for 2008

Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis

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LONG-TERM GOALS

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at the scales that control how they live, reproduce, and die.

OBJECTIVES

We are working with our collegues in the ONR-sponsored research program on Layered Organization in the Coastal Ocean (LOCO) to jointly analyze data collected in Monterey Bay, CA during FY2002, 2005 and 2006. Our work this year has involved data analysis, presentation of our results at several scientific meetings, and the preparation of publications.

APPROACH

During the late summer and early fall of 2005 and 2006, very thin layers of phytoplankton, zooplankton, and water column physical structure were studied by a part of the LOCO research team at several closely spaced shallow, near-shore stations in

northeastern Monterey Bay. Other team members examined larger scale horizontal distributions and temporal thin layer patterns in deeper water nearby, while still others collected plankton and made measurements of turbulence, nutrients and various optical properties of the water column. Our part of this research involved the deployment of several acoustic and ancillary sensors on the seabed. The acoustic sensors were used to describe the distributions of small zooplankton, micronekton and small gas bubbles. Other LOCO principal investigators also used a variety of sensors to examine thin layers and the conditions and processes that led to their formation and destruction during each of the field periods in Monterey Bay. We have been analyzing and sharing our data, comparing it to measurements made by our colleagues, making presentations at technical meetings, and submitting papers for publication.

WORK COMPLETED

We have analyzed acoustical and environmental data collected in Monterey Bay during each of the LOCO field periods. Specific data sets, especially several that were of special interest to both us and our colleagues who are concerned with the optical signatures of thin layers were analyzed in detail to support the preparation of invited presentations and papers for publication. We also met with most of the LOCO principal investigators in Orlando, FL before the 2008 Ocean Sciences Meeting, where we compared data sets. Selected results from our research have been presented via invited papers at a special session on thin layers at the ASLO/TOS/AGU meeting in Orlando, FL and as an introduction to a session on ecosystem monitoring at the ICES Symposium on the Ecosystem Approach with Fisheries Acoustics and Complementary Technologies (SEAFACTS) in Bergen, Norway in June 2008.

RESULTS

Since the LOCO research program is in the data synthesis phase, the following discussion is a short summary of results for some of the data analyses carried out cooperatively by Van Holliday, Charles Greenlaw, Percy Donaghay, Jim Sullivan, and Jan Rines. Some elements of the discussion below are the subject of a paper now in review for a special issue of the ICES Journal of Marine Science during the summer of 2009 (Holliday et al. [submitted, 2009]).

Although temperature and salinity fine-structure has long been known to exist in the sea, the processes that lead to the formation of thin acoustic scattering layers are less well known. Closely spaced vertical profiles collected either by high frequency echo sounders during a transect, or by a bottom-mounted, up-looking sounder as water moves over the sensor, often reveal acoustic scattering layers with thicknesses of tens of centimeters to a few meters. Sometimes these layers are coincident with a particular isopycnal, isotherm or salinity surface. At other times they do not appear to be tightly associated with any parameter that we have measured. Volume scattering strengths are displayed in Figure B1 at two minute intervals for a 24-hour interval between beginning at noon August 26, 2005 in Monterey Bay, CA. This volume scattering strength (Sv) record is from the 700 kHz

channel of a TAPS-6 deployed in a bottom-mounted, up-looking mode. The TAPS-6 is a multi-frequency acoustic sensor specifically designed to study zooplankton and micronekton. Sampling was done with a vertical resolution of 12.5 cm at intervals of 2 min. Temperature contours are overlaid as measured by a thermistor chain, located nearby. Those samples were also collected at 2 min intervals.

Scatterers located near the surface during daylight hours were observed to migrate to the depths of two specific isotherms (14.2 and 13.0 °C). The migration started slowly at sunset (19:45 Pacific Daylight Time) and for the next hour was only visible in the top 2 m. At 20:45 PDT (30 min after nautical twilight), the downward migration began in earnest. The first cohort of migrators reached the 14.2 °C isotherm at 21:10 and remained very near that isotherm in a 30 cm thick scattering layer until 23:00 PDT, after which the layer began to thicken and then disperse upward. Acoustic inverse methods were used to determine the size-abundance spectrum for scatterers in the water column (Holliday 1977; Costello, Pieper and Holliday 1989). For the shallower of the two layers, at the 14.2 °C isotherm, we determimed that the scattering was likely caused by two kinds of migrating organisms. The most abundant were 1 mm long copepods with a biovolume of 35,000 mm3 m-3. One millimeter long Acartia tonsa were collected within a meter of the sea surface during the daytime, before the evening migration. Additionally, elongate scatterers with a length of 3.6 mm were detected with an estimated biovolume of 14,000 mm3 m-3.

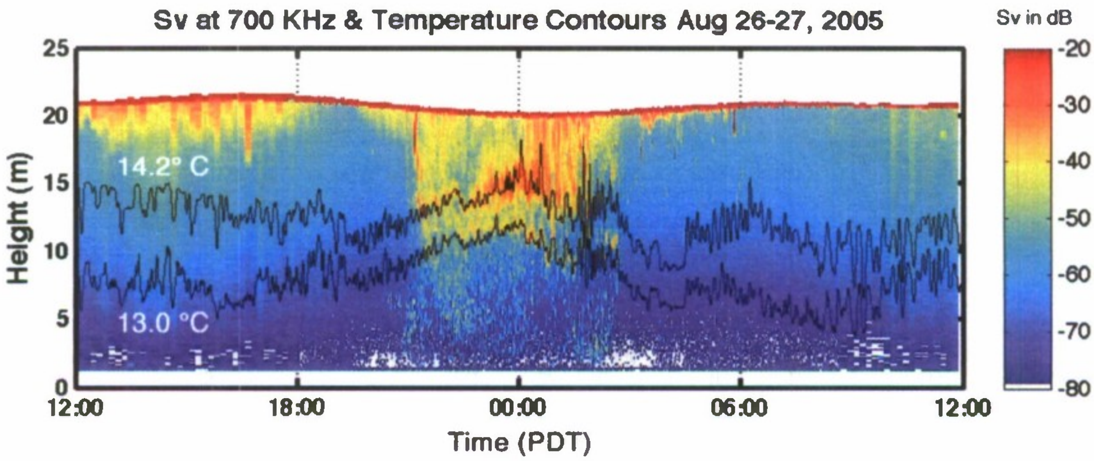

Figure B1: . Volume scattering strengths, measured at 2 minute intervals are displayed for a 24-hr period between noon, Aug. 26 and noon, Aug. 27, 2005. A downward vertical migration from above 50 cm below the sea's surface started at dusk on the 26th. As a result, a thin acoustic scattering layer quickly formed on the 14.2 °C isotherm and a second layer formed about an hour later on the 13.0 °C isotherm. These two layers closely tracked these isotherms until scatterers gradually began returning to the surface. All scatterers were back at the surface by 03:00 PDT, well before sunrise at 06:34 PDT.

The second cohort of scatterers may have left the surface at a slightly later time than the first group. In any case, they swam downward at a slower rate and passed through the 14.2 °C isotherm, settling on the 13.0 °C isotherm at *ca.* 23:20 PDT. They remained on that isotherm until *ca.* 01:40 PDT and then quickly returned to the surface. This deeper of the two scattering layers also contained considerably less biomass. Only 750 $mm^3\ m^{-3}$ of the 1 mm long copepods and 300 $mm^3\ m^{-3}$ of the 3.6 mm elongate scatterers were necessary to explain the volume scattering strengths measured in that layer. The scatterers in the deeper of these two layers (at the 13.0 °C isotherm) left for the surface at *ca.* 02:40 PDT. Within *ca.* 20 min, all scatterers that had migrated into the water column at, and just after dusk, had arrived at the sea surface. A few migrators had bypassed both isotherms and dispersed in the lower half of the water column. Those scatterers also returned to the surface before 03:00 PDT. This was well before sunrise at 06:34 PDT.

Hourly ORCAS profiles were also collected at this site by Percy Donaghay's research team (Figure B2, contour overlay). Estimates of the Chl-a profiles were derived from ac-9 measurements of absorption at 650 and 676 nm using the method documented by Sullivan *et al.* 2005. Those hourly profiles were contoured and are overlaid on the TAPS-6 700 kHz Sv data for the same period. Although contours between measurements are interpolated and could vary from the true values between samples, contours have been constrained to pass through measured data points collected on the hour. Examination of the estimates of Chl-a indicate minimal correlation with the volume scattering profiles collected during the same interval of time. An ORCAS profile collected at midnight, just after the second thin acoustic scattering layer had arrived at the 13.0 °C isotherm, revealed that there was a strong Chl-a peak (> 20 μg/l) at the base of the seasonal thermocline, *between* the 14.2 and 13.0 °C isotherms (Figure B2, *ca.* 12 m above the seabed, at 00:00 hrs.).

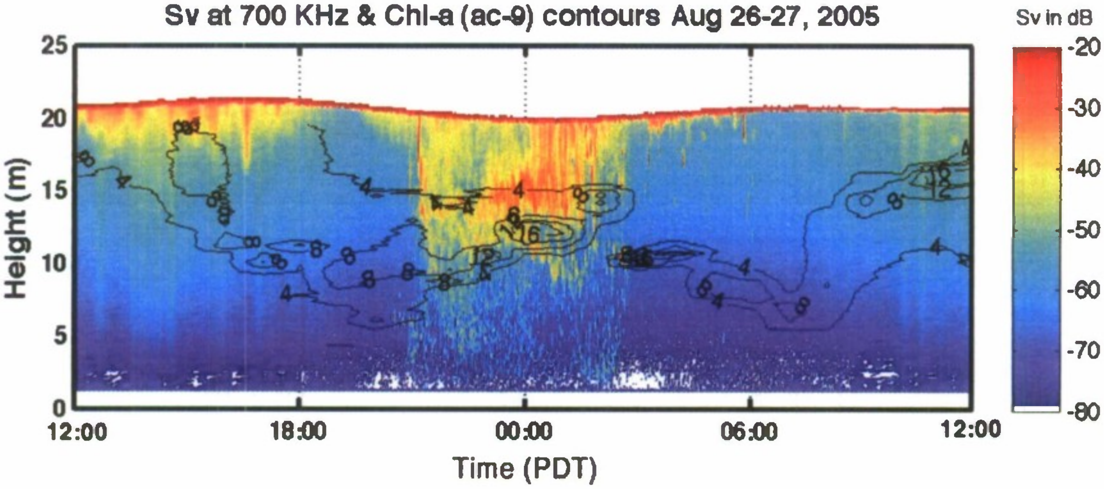

Figure B2: The volume scattering strength profiles of Figure B1 are overlaid with estimates of Chl-a derived from an ac-9 aboard an ORCAS profiler deployed near the

TAPS-6. Chl-a levels are not well correlated with Sv measurements. The peak Chl-a level during the time when acoustic scattering layers were present in mid-water occurred just after midnight at a height above the bottom of ca. 12.5 m. This location was between the two zooplankton layers. Chl-a data provided by Percy Donaghay and Jim Sullivan.

Estimates of the slope of the optical attenuation coefficient derived from the ORCAS profiler data for this layer suggests the presence of larger particles in the layer than are present in the water just above or below the layer. A time record of hourly data from the ORCAS sensor package, along with samples collected at the surface during the day, revealed that the thin Chl-a layer was associated with the dinoflagellate *Akashiwo sanguinea*. During our occupation of the Monterey Bay study site, this organism migrated to successively deeper depths each night in order to reach the nutricline and returned shallower depths, presumably for better access to sunlight during the day. The size of this organism, *ca*. 70 microns, is consistent with the optical estimates of length for the Chl-a layer detected with the ac-9. The smaller particles above and below this layer included a diverse collection of small diatoms of different species.

Although one can often associate the presence of a thin acoustic scattering layer with vertical structure in the physics or chemistry of the water column, or with the presence of potential prey, it is also not unusual for thin acoustic scattering layers to be located at depths not obviously associated with such fine-structure. This suggests that zooplankton and micronektion may be responding to as yet undiscovered stimuli or combinations of environmental conditions that they perceive to be optimal. Alternatively they might be avoiding conditions or organisms they view as threatening. In any case, our observations suggest that zooplankton behavior should not be ignored when considering processes leading to the formation of thin acoustic scattering layers. In fact, it is not at all unusual to observe multiple layers forming at the same location with different processes appearing to be active at different depths. On July 18-19, 2006 a thin layer of warm water appeared in the top 2 m of the water column at one of our TAPS deployment sites in Monterey Bay. There was also a deeper pycnocline in mid-water (Figure B3).

A warm, light shallow layer was observed near the surface at sunset and it disappeared about dawn. Its presence may have been associated with the tidal flow, wind driven advection, or both. A thin, strong acoustic scattering layer formed on the steep density gradient at the base of this lens of warm water. The main pycnocline was located on a sigma-t surface of *ca*. 25.6 in midwater. Although the pycnocline was not always sharply defined, the deeper acoustic scattering layer did not appear to be tightly coupled to this density surface. Thus, in data from the same day, two different migratory patterns for the zooplankters were observed. In one case, a layer formed on, and closely tracked a shallow temperature and density gradient. In the other, the acoustic scattering layer migrated through the strong thermocline, forming a thin scattering layer several meters deeper in the water column. The upward migrations for both layers, but especially from the one in midwater began and were completed before sunrise.

The relative irradiance (bottom panel, Figure B3) illustrates that while downward migrations at the shelf location in Monterey Bay in the summer were consistently triggered by the arrival of dusk, the main migration was often delayed beyond that time. On the day shown, the shallow scattering layer dispersed at sunrise, but the deep layer had already dispersed hours earlier. In many cases, however, when multiple layers were present, both dispersed, often via with a rapid migration to the surface, long before dawn.

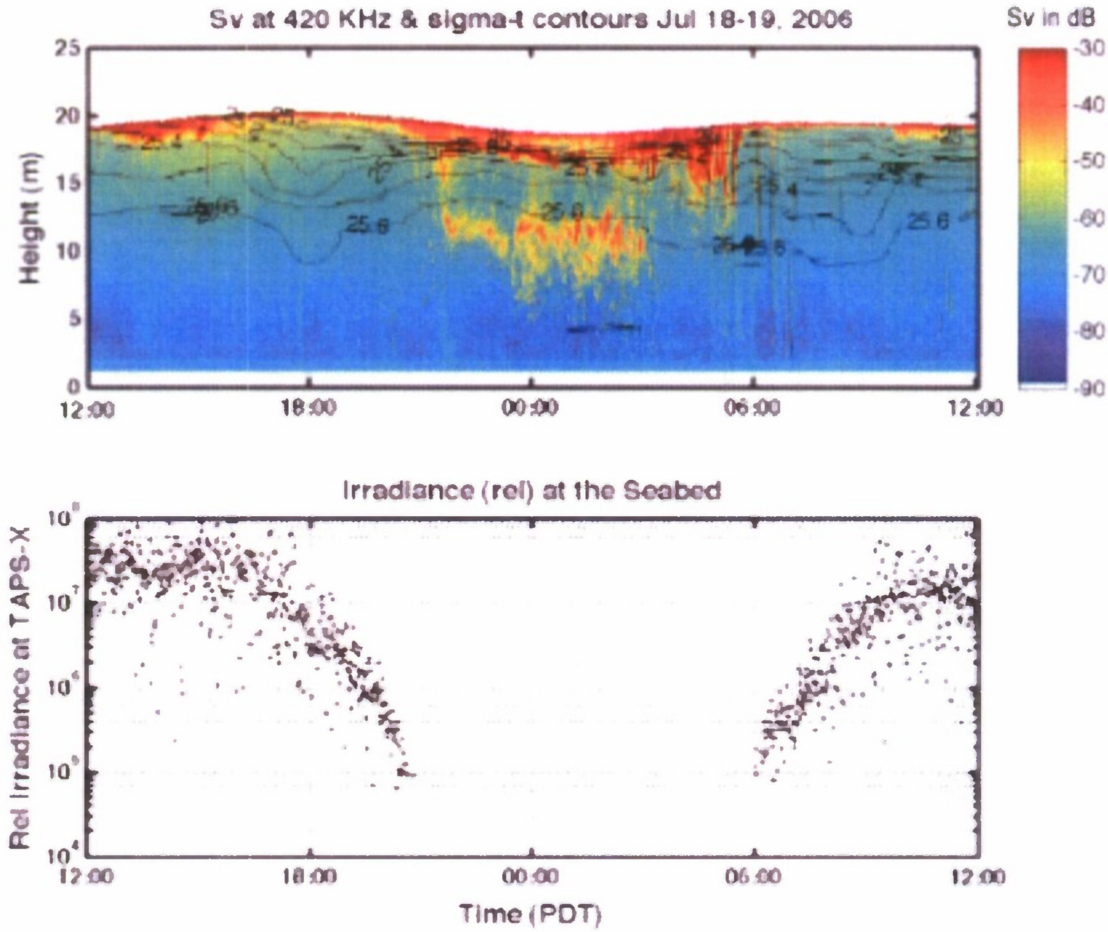

Figure B3: Volume scattering strength profiles (Sv) at 420 kHz are displayed at 2 min intervals from noon July 18 through noon July 19, 2006 versus height above an up-looking multiple frequency TAPS sensor mounted on the seabed (top panel). Sigma-t contours are overlaid (ORCAS data courtesy of Percy Donaghay and Jim Sullivan). Relative irradiance at the seabed is illustrated in the bottom panel. Two acoustic scattering layers appeared at sunset, one of which remained above ca. 2 m depth. The other rapidly descended into the water column, where it was visible between 10 to 14 m above the seabed until about 03:00 PDT.

At first glance, the observed patterns of zooplankton and phytoplankton migration in Monterey Bay during 2005 and 2006 seem very complex, however, some features appear to be quite consistent from day-to-day. We continue to examine measured patterns in acoustic scattering, dynamic diel changes in zooplankton distributions derived from the TAPS data, patterns in fluorescence and optical scattering and attenuation, the physical structure of the water column as measured with Donaghay's ORCAS profilers, and samples of the phytoplankton, in an attempt to understand what is driving the most common, repeated features in the patterns of vertical migration.

Although our analyses of the LOCO data are ongoing, we can draw several conclusions from our observations in Monterey Bay and other coastal locations.

Phytoplankton and zooplankton in open coastal systems can and do form decimeter (and smaller) scale layers. Since these layers may contain as much as 80% of the water column biomass for each trophic level, it is likely that they affect the the biological dynamics of these ecosystems.

LOCO investigators have found that phytoplankton, protists, microzooplankton, zooplankton, micronekton and fish larvae sometimes aggregate on physical or water mass boundaries forming thin layers. Often they are found at other locations in the water column as well. Not all thin layers are co-located with physical structure in the water column. Some thin layers appear to form as the result of organism behavior.

Finally, if predator and prey are to interact, they must spend time together. At our study site, an energy transfer model that assumed that zooplankton nighttime foraging began at sunset, lasted until sunrise, and was proportional to the total Chl-a in the water column would have been very questionable. At this site at least, unless one looked with sufficiently high temporal and spatial resolution at how vertical profiles of phytoplankton and secondary producers changed and interacted, it is likely that attempts to model the transfer of energy between the two trophic levels in a simple way would have led to serious errors in estimates of grazing. Trophic models that do not take vertical fine-structure and zooplankton behavior into account may sometimes be attractive, elegant, and simple, but in Monterey Bay during the time we were making observations they would also have led to incorrect conclusions. Most of the time, secondary producers tended to ignore the organisms associated with the highest Chl-a distributions, preferring to co-locate and presumably forage on a collection of diatoms exhibiting lower levels of Chl-a. Additionally, the depth history of migrating zooplankton and micronekton was complex, depending on not only diel changes in light levels and the vertical distribution of phytoplankton, but also on the horizontal advection of fine-scale vertical structure in temperature and salinity. Our preliminary analyses also suggest the possibility that the vertical migration history for zooplankton can be influenced by the vertical distribution of phytoplankton that can be toxic (e.g., *Alexandrium catenella*).

IMPACT/APPLICATIONS

Our results strongly suggest that fine-scale vertical structures in marine plankton are ecologically important features in the upper part of the water column. When thin plankton layers are present, food densities appear to rival or even exceed those in the traditional chlorophyll maximum (Cassie 1963; Lasker 1975; Mullin and Brooks, 1976) and in zooplankton patches (Steele 1976). As such they are a mechanism for creating concentrations of food at scales necessary for the survival of individual fish larvae (Jones 1973). For a population of some species of fish, the widespread occurrence and persistence of thin layers at the time of first feeding could mean a good year class, or a very poor one. Although their occurence is seasonally dependent on local physical oceanography (e.g., upwelling and relaxation) in some coastal locations, thin layers appear to be widespread and frequently present in coastal zones. Although further study is needed to conclusively support their frequent occurrence offshore, our prior experiences with the use of high frequency sensors such as MAPS (the Multifrequency Acoustic Profiling System) suggests that thin layers may well occur in deep offshore water as well as on the continental shelf. Mechanisms for their formation, maintenance, and destruction will likely vary according to an area's physical and biological environments.

Our acoustical data, especially when viewed alongside synoptic optical data, strongly suggest that plankton behavior, especially diel vertical migration, can strongly contribute to the formation of thin plankton layers. However, the same acoustical and optical data also reveal that the interactions between phytoplankton, zooplankton, fish, and physio-chemical ocean fine structure is extremely complex. The sensors used in the LOCO research program have provided us with detail regarding fine-scale structure in the marine ecosystem and dynamic interactions that has never previously been available for critical examination.

As aggregating mechanisms, thin layers clearly impact food availability for several trophic levels and they are critical for larval organisms before they are able to swim and forage effectively. Even after horizontal swimming is possible, when such layers are present there is an advantage for local foragers since simple vertical migration will bring about an encounter with a layer. We suggest that horizontal migration to find patches is more challenging and less likely to be productive than is vertical migration for fish larvae and even for juveniles.

TRANSITIONS

Much of the multi-frequency technology that we developed under sponsorship of ONR has been transitioned to the measurement of zooplankton size and abundance from moorings deployed in the North Pacific and Bering Sea areas by NOAA's National Marine Fisheries Service / Alaska Fishery Science Center and the Pacific Marine Environmental Laboratory (PMEL). Multiple frequency echo sounders and sonars have also found widespread use for fisheries assessment purposes. We were recently recognized for having played a significant role in introducing multifrequency acoustics to the fisheries management community (see Honors/Awards/ Prizes/, below). This transition would not have been possible without ONR's support in developing multifrequency acoustical technology.

RELATED PROJECTS

We continue to support NOAA's Alaska Fisheries Science Center and NOAA's Pacific Marine Environmental Laboratory personnel by processing the TAPS-8 data being telemetered from the Bering Sea. A significant part of the development of the TAPS sensor technology was funded by ONR. The effort is funded by NOAA's Coastal Ocean Program. Our co-PIs at NOAA have now collected three years of data from the Coastal Gulf of Alaska (CGOA) and three years of data from the M2 mooring on the Bering Sea shelf, north of the Aleutian Islands. We will be assisting NOAA in the processing and publication of papers related to the collection of those data, which are now transmitted to shore hourly via the Iridium satellite network. We have prepared a manuscript based on the CGOA data set and are organizing at least one additional publication that will deal with the Bering Sea data.

One of the PIs (Holliday) has served for the last three years on the scientific organizing committee for the International Symposium on the Ecosystems Approach with Fisheries Acoustics and Complementary Technologies (SEAFACTS) in Bergen, Norway, 16-20 June 2008. He was invited to open the SEAFACTS session on Ecosystems and Fisheries Monitoring Session with a presentation designed to focus on the role of technology in support of an ecosystems approach to fisheries management. That presentation featured some of the LOCO data from Monterey Bay, CA. Data from the ONR sponsored LOCO DRI were used to illustrate ways in which acoustical estimates of zooplankton biomass profiles, and optical estimates of biomass profiles of phytoplankton could be used to advance ecosystem-based fisheries management. Several LOCO participants, i.e., Holliday, Donaghay, Greenlaw and Sullivan, have, along with Jeff Napp, prepared a paper on this subject. It has been submitted for peer review and possible inclusion in a special issue of the ICES Journal of Marine Science.

REFERENCES

Cassie, R.M. 1963. Microdistribution of plankton. Oceanogr. Mar. Biol. Ann. Rev. 1: 223-252.

Costello, J.K., R.E. Pieper, and D.V. Holliday. 1989. Comparison of Acoustic and Pump Sampling Techniques for the Analysis of Zooplankton Distributions. J. Plankton Res. 11(4): 703-709.

Holliday, D.V. 1977. Extracting Bio-Physical Information from the Acoustic Signatures of Marine Organisms. In Ocean Sound Scattering Prediction, N.R. Anderson and B.J. Zahuranec, Eds. Marine Science Series Vol. 5, Plenum Press, New York, NY, pp. 619 - 624.

Jones, R. 1973. Density dependent regulation of the numbers of cod and haddock. Rapp. P.-v. Reun. Cons. perm. int. Explor. Mer 164, 156–173.

Lasker, R., 1975. Field criteria for survival of anchovy larvae: The relation between inshore chlorophyll maximum layers and successful first feeding. Fish Bull. 73: 453-462.

Mullin, M.M. and Brooks, E.R., 1976. Some consequences of distributional heterogeneity of phytoplankton and zooplankton. Limnol. Oceanogr. 21: 784-796.

Steele, J.R. 1976. Spatial patterns in plankton communities. Plenum Press, New York, 470 pp.

Sullivan, J.M., Twardowski, M.S. Donaghay, P.L. and Freeman, S. 2005. Using optical scattering to discriminate particle types in coastal waters. Applied Optics, 44(9): 1667-1680.

PUBLICATIONS

Cheriton, Olivia M., Margaret A. McManus, D.V. Holliday, Charles F. Greenlaw, Percy L. Donaghay, and Tim Cowles. 2008. Effects of mesoscale physical processes on thin zooplankton layers at four sites along the west coast of the U.S. Estuaries & Coasts 30(4): 575-590 [refereed].

Anderson, J. T., Holliday, D.V., Kloser, R., Reid, D. G., and Simard, Y. 2008. Acoustic seabed classification: current practice and future directions. ICES Journal of Marine Science 65: 1004-1011. [refereed].

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. In *The Future of Fisheries Science in North America*, Fish & Fisheries Series, Vol. 31. Beamish, Richard J. and Rothschild, Brian J. (Eds.). ISBN: 978-1-4020-9209-1, *ca.* 450 pp. [in press, referred].

Holliday, D.V., P.L. Donaghay, C.F. Greenlaw, J.M. Napp, and J.M. Sullivan. 2009. High-frequency acoustics and bio-optics in ecosystems research. ICES Journal of Marine Science (Special Issue – Summer 2009). [submitted, referred].

HONORS/AWARDS/PRIZES

The International Council for the Exploration of the Sea (ICES) presented its first Prix d'Excellence Award to Van Holliday in Halifax, NS, Canada during its Annual Science Conference in September 2008. The description of this award is as follows. The award recognizes the highest level of contribution to the ICES vision of "An international scientific community that is relevant, responsive, sound, and credible, concerning marine ecosystems and their relation to humanity". Recipients of this award need not be associated with ICES, although their work must be relevant to the mission of ICES. They will have contributed through their research, scientific leadership, and/or leadership in the objective application of science to policy for sustained use and conservation of marine ecosystems. Innovation, teamwork, mentoring, and objective communication with the

public must exemplify the career of the recipient. The ICES Prix d'Excellence Award will generally be made no more often than every third year, and then only if there is an appropriate candidate.

Appendix C: Annual Progress Report for 2009

Layered Organization in the Coastal Ocean: Acoustical Data Acquisition, Analyses and Synthesis

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LONG-TERM GOALS

The long-term goal of our research is to improve our ability to observe the ocean's plants, animals, and their physical and chemical environment at the scales that control how they live, reproduce, and die.

OBJECTIVES

We have been working with our collegues in the ONR-sponsored departmental research initiative (DRI) on Layered Organization in the Coastal Ocean (LOCO) to jointly analyze data collected in Monterey Bay, CA during FY2002, 2005 and 2006. Our work this final year of the project has been focused on data analysis and the preparation of publications.

APPROACH

In 2002 we collaborated with Percy Donaghay (URI/GSO) and Margaret McManus (UCSC) in a series of "Quicklook" surveys of coastal locations around the US designed to find a location in which an intensive study of thin plankton layers could be conducted by a larger group of investigators. One of those locations was in the northeast corner of

Monterey Bay, CA on the Pacific Coast of the USA. During the late summer and early fall of 2005 and 2006, very thin layers of phytoplankton, zooplankton, and water column physical structure were studied by a part of the LOCO research team at several closely spaced shallow, near-shore stations in northeastern Monterey Bay (Figure C1). Other LOCO project participants examined larger scale horizontal distributions and temporal thin layer patterns in deeper water offshore in the bay, while still others collected plankton and made measurements of turbulence, nutrients and various optical properties of the water column. Our part of

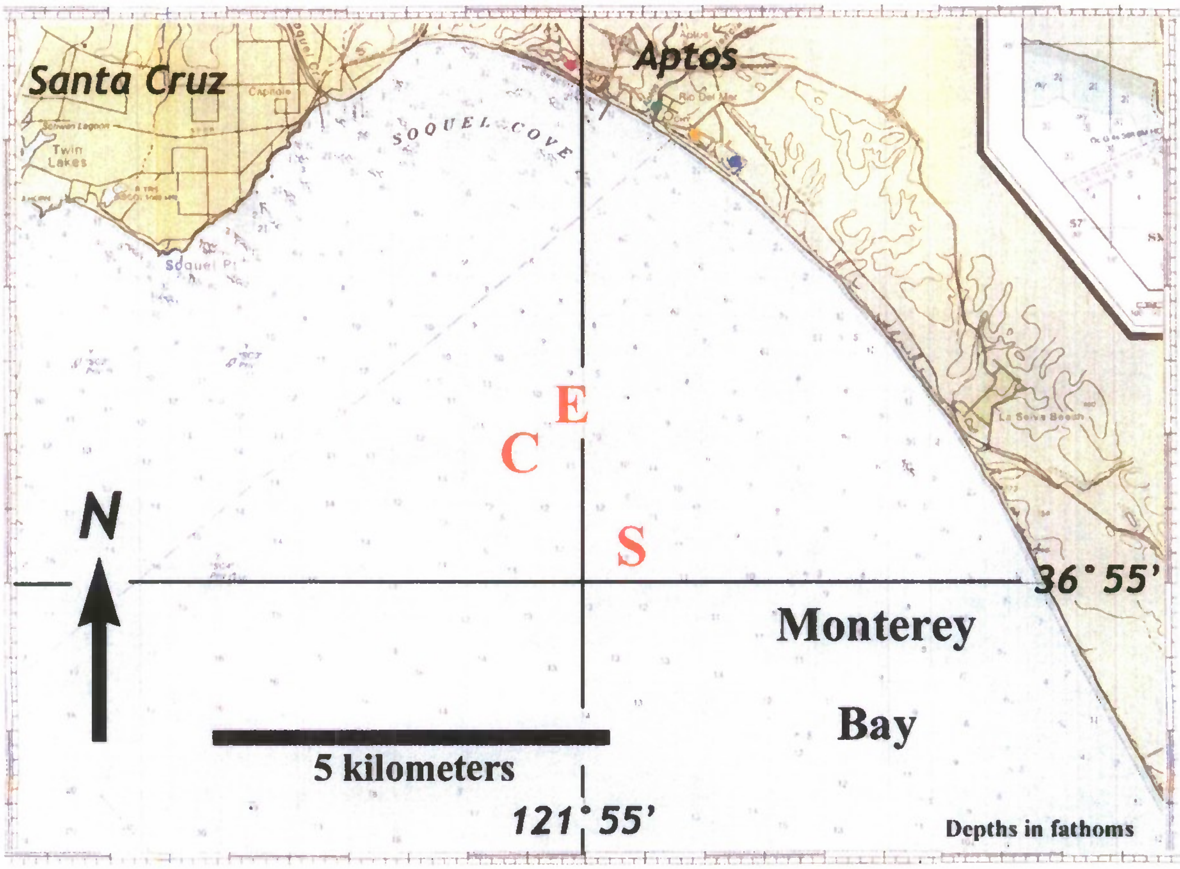


Figure C1: Chart showing station plan showing the locations of the LOCO moorings in an array located in northeastern Monterey Bay, CA USA. The measurements made in 2002 were at Station C. Station C was located about 5 km south of the city of Aptos and about 12 km southwest of the main business district in the city of Santa Cruz. In 2005, the moorings were located at Stations C, E, and S as indicated in this chart. The station labeled S in 2005 was moved to the north by about 1 km for the 2006 work. Water depths at these stations ranged from 18.3 m at the inshore stations (E and S) to 20.1 m at Station C.

this research involved the deployment of several acoustic and ancillary sensors on the seabed. One of these, an upward profiling multifrequency acoustic zooplankton sensor, the Tracor Acoustic Profiling System or TAPS is displayed in Figure C2.

Figure C2: A TAPS (Tracor Acoustic Profiling System) is shown on the fantail of the R/V Shana Rae. A spar buoy has been deployed and can be seen in the upper left quadrant of the picture. The spar buoy carries a navigation light, a VHF antenna and a radio to support 2-way telemetry between the TAPS (vertical black cylinder) and a shore station in Aptos, CA, about 5.5 km to the north of the instrument array. The acoustic transducers are located on the top of the TAPS. Several TAPS configurations were used in the array of fixed sensors during this series of research cruises. The least number of discrete acoustic frequencies employed was 6 and the most was 72. The acoustic operating band in which acoustic volume scattering strength profiles were collected varied with the specific TAPS that was deployed, but nominally ranged from 0.165 MHz to 3 MHz. Volume scattering strengths measured by the TAPS and telemetered to shore in 12.5 cm depth intervals allow one to estimate the abundance and size spectra for the water column zooplankton. A thermistor is also located on the bottom endcap of the TAPS and reports the water temperature just above the seabed. Depending on the deployment, up to 16 thermistors were located on the mooring line between the spar buoy and a weight on the seabed. Sensors for measuring downwelling light were also located near the top of the mooring frame. The blue boxes in the bottom of the mooring frame contain rechargable batteries.

Our acoustic sensors were used to describe the distributions of small zooplankton, micronekton and small gas bubbles. Other LOCO investigators used a variety of moorings, ship-borne, and glider-borne sensors to examine thin layers and the conditions and processes that led to their formation and destruction during each of the field periods in Monterey Bay. In this final year of the project we have been analyzing and sharing our data and results, comparing it to measurements made by our colleagues, making presentations at technical meetings, and submitting papers for publication.

WORK COMPLETED

During the period covered by this grant (to URI) and a predecessor contract (to BAE Systems), we collected and analyzed acoustical and environmental data from a coastal site in Monterey Bay during several weeks in each of three years. The focus of our research was to describe and try to understand the processes that lead to the formation, maintenance, and destruction of thin layers of zooplankton. In addition to the preparation of several publications dealing with thin zooplankton layers, we shared our data on the distribution and temporal changes in the distribution of zooplankton with our colleagues in the LOCO research program. VHF telemetry allowed us to collect, process and display multi-frequency acoustical volume scattering strength data from several moorings in near real-time. These data were made available to our LOCO colleagues daily via the project web site, and in real time when needed to support decisions about locations, depths and times of directed sampling efforts designed to collect plankton from these fine-scale vertical structures. Environmental data, e.g., water columm temperature profiles that did not have telemetry were processed and distributed for use by other investigators on retrieval of the sensors.

The remainder of our effort involved detailed analysis and interpretation of the data we collected during time intervals of special interest to several other LOCO researchers. We also identified several times during which our own data suggested that repetitive zooplankton patterns were occuring daily (Figure C3). Additional intervals were identified during which unique or previously unobserved patterns appeared. These time intervals then became the focus of intense analysis by the investigators with overlapping data in time and space. The observations and interpretations we were able to make collectively about the dynamics of thin layers during these intervals were shared with our LOCO colleagues, presented at several scientific meetings, and documented in the publications listed in this report. Additional publications including our data as well as those of our LOCO colleagues are in preparation for a special issue of Continental Shelf Research.

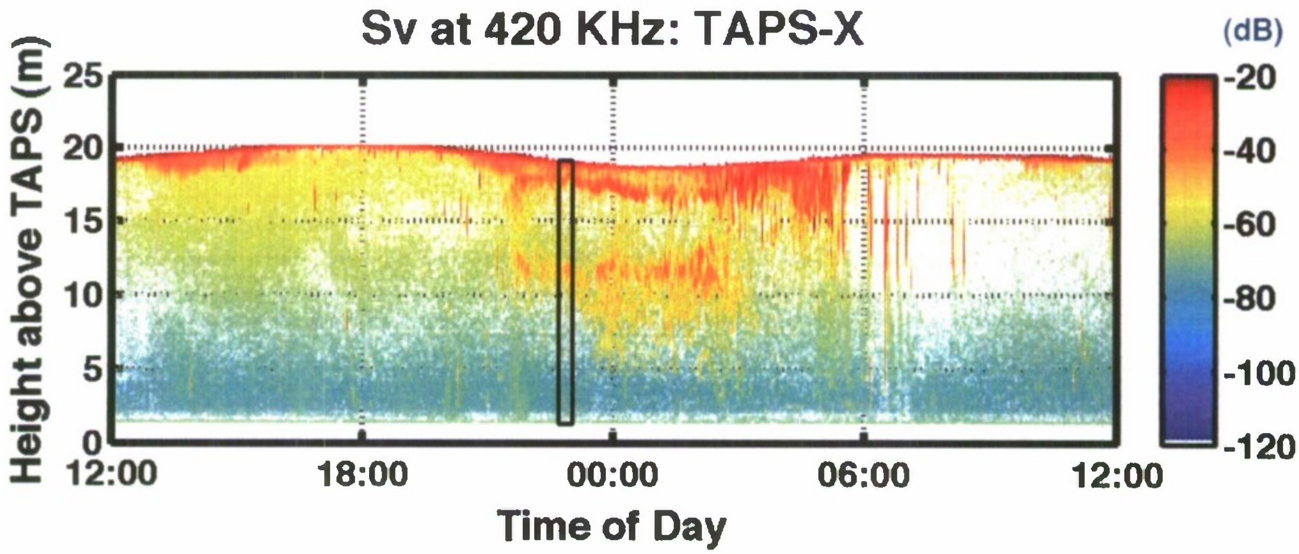


Figure C3: Volume scattering strengths are displayed versus height off the seabed to the surface at ca 20 m in this 420 kHz TAPS record from noon on July 18 to noon on July 19, 2006. The data were collected during the LOCO experiment in the northeast corner of Monterey Bay, CA on the shelf. The variation in the location of the surface echos is due to the tides. Two thin layers are present, one at ca. 2-3 m below the surface and the other in mid-water at ca 11-12 m above the bottom. Volume scattering in both layers was between -55 and -35 db re 1 microbar at 1 m. Before about 2100, the zooplankton that caused the scattering were located within 1 m (or closer) of the sea surface. Just after 2100 (near the time of sunset) the organisms executed a reverse migration into the water column with one layer remaining shallow and the other moving into mid-water. The deeper layer began its upward migration before 0300 and disappeared from the water column by 0330. The shallow layer had moved to within 25 cm of the surface by 0600. Acoustic inverse results calculated from six frequency data measured between 1203 and 1221 (box) revealed that both layers contained scatterers that resemble fluid spheres (acoustically) and elongate scatterers such as krill. Several sizes of small gas bubbles were also present in each layer, as well as between 1 and 4 m above the seabed and very near the sea surface.

RESULTS

The following points summarize some of the main conclusions we have reached during our LOCO research. For more information, the interested reader is referred to the references below as well as to those cited in our publications.

- Thin acoustic scattering layers are common features in the coastal ocean, having been observed on both US coasts and in the Gulf of Mexico.
- Thin acoustic scattering layers may persist at a particular location for times varying from hours to weeks.
- Most thin acoustic scattering layers result from vertical structure in zooplankton concentrations.
- Zooplankton thin layers often co-occur with thin phytoplankton layers.
- Zooplankton sometimes avoid thin phytoplankton layers, creating thin layers of acoustic scattering above, below, or both above and below a thin phytoplankton layer. This behavior is not unusual.
- Zooplankton often migrate vertically at dusk, creating thin acoustic layers in the water column. These layers often stop at thermoclines or pycnoclines and follow them closely for hours. Both normal (from deeper waters toward the surface) and reverse (from near the surface downward) vertical migrations have been observed. In the case of reverse migration, the layers sometimes disperse and move upward long before sunrise. This suggests that some migrations are terminated by the time

of satiation rather than by light. The migrators do not necessarily all start either up or down from within a thin zooplankton layer at the same time. In some cases, we have observed the upward dispersal of a thin zooplankton layer to have been caused by a shoaling pycnocline.

- While less numerous than zooplankton thin layers in our observations, acoustic scattering layers have also been observed with multifrequency spectra suggesting that they are the result of thin distributions of very small bubbles (1 to 50 microns in radius) in the vertical. The scattering specra of some of these layers can only be explained by a mix of zooplankton and small gas bubbles. We suggest two hypotheses: 1) bubble layers may be generated *in situ* within thin layers of zooplankton and phytoplankton when the water becomes supersaturated with oxygen due to photosynthesis by the phytoplankton in the layer, and 2) rising bubbles may become aggregated into thin layers having a biological origin (e.g., marine snow) or at physical boundaries such as sharp density gradients as they rise from below. We have observed bubbles in the water column that are clearly the result of natural methane seeps (e.g., off Coal Point at Santa Barbara, CA). We have also observed small bubbles, possibly the result of decay processes on the seabed rising towards the surface in West Sound, Orcas Is., WA. We also hypotheisze that small bubbles of oxygen may be generated by photosynthesis in shallow, sandy seabed. Additional studies would be needed to fully understand the mechanisms by which thin bubble layers can be created and their frequency of occurence.

IMPACT/APPLICATIONS

As a result of this work, we have an improved the understnding of how the temporal and spatial characteristics of fine-scale vertical structure in marine zooplankton interact with distributions at similar scales in phytoplankton and the physical environment. The data suggest that fine-scale vertical structures in marine plankton are ecologically important features in the upper part of the water column. Our observations, and those of our LOCO colleagues, are a step forward in pursuit of our long-tern goal of predicting the acoustical, optical and ecological consequences of these critical scale structures. Thin zooplankton layers appear to be widespread and frequently present in coastal zones. When present they can rival traditional sources of food for fish and fish larvae such as are found in the seasonal chlorophyll maximum (Cassie 1963; Lasker 1975; Mullin and Brooks, 1976) and in zooplankton patches (Steele 1976). As such they are a mechanism for creating concentrations of food at scales necessary for the survival of individual fish larvae (Jones 1973). For some species of fish their presence at the time of first feeding could make the difference between a good year class and a poor one. This suggests that future ecosyetem models should include a mechanism for linking spatial patterns of populations and communities to habitat characteristics at sub-meter vertical scales.

On several occasions we have observed a pattern of avoidance for zooplankton when they encounter some thin phytoplankton layers. While our sampling of the phytoplankton has necessarily been limited, we have determined that the presence of some potentially harmful species of phytoplankton may play a role in this avoidance behavior. This suggests that modelers attempting to predict the onset and duration of harmful algal blooms should consider the impacts of reduced grazing by zooplankton on thin phytoplankton layers when such species may be present.

Finally, the density of zooplankton and phytoplankton in thin layers often exceeds the average values in the water column by orders of magnitude. In some of our observations, we have detected acoustical scattering in that can be best explained by the presence of very small gas bubbles. Bubble layers have been detected at depths where the water is supersaturated by oxygen as well as at other depths. At least two mechanisms are suggested. One involves the generation of gas bubbles by photosynthesis in thin layers. The other suggests that rising bubbles, formed from either decay or photosynthesis in or on the seabed may be trapped by the constiuents of thin layers of biological material in thin layers. Those who model the performance of naval systems that use acoustical and optical technologies may wish to consider how these sub-meter thick biological structures can impact operational systems and those being planned for the future.

TRANSITIONS

Much of the multi-frequency technology that we developed under sponsorship of ONR has been transitioned to the measurement of zooplankton size and abundance from moorings deployed in the North Pacific and Bering Sea areas by NOAA's National Marine Fisheries Service / Alaska Fishery Science Center and the Pacific Marine Environmental Laboratory (PMEL). Moorings in the Coastal Gulf of Alaska (CGOA) successfully gathered data for four to five month periods during 2002, 2003 and 2004. The duration of these deployments were dictated by operational ship schedules at the NMFS/AFSC and NOAA/PMEL laboratories. Funding for the CGOA work was provided as a part of NOAA's Coastal Ocean Program's GLOBEC initiative. Starting in

2006, TAPS were employed on moorings established on the shelf in the eastern Bering Sea. Those programs continue to the present time, with moorings being deployed during the ice free part of the year. During the last three years, satellite telemetry has allowed us to collect and distribute data sets spaced at twenty minute intervals each hour (http://www.ecofoci.noaa.gov/projects/TAPS8/efoci_TAPS8devel.shtml and http://www.ecofoci.noaa.gov/projects/TAPS8/efoci_TAPSzooplankton.shtml).

Multiple frequency echo sounders and sonars have also found widespread use for fisheries assessment purposes. We were recently recognized for having played a significant role in introducing multifrequency acoustics to the international fisheries management community. This transition would not have been possible without ONR's support in developing multifrequency acoustical technology.

RELATED PROJECTS

The LOCO (Layered Organization in the Coastal Ocean) work done under this grant was an integral part of an ONR Departmental Research Initative (DRI) that was designed to examine the characteristics, creation, evolution, and dissipation of thin biological layers and related physical and chemical structures in the marine environment. Our work focused on thin zooplankton layers and the role that they may play in the marine ecosystem. While the work was done in the coastal zone, these layers have been detected, but not throughly studied, in deep water as well. The LOCO group included scientists and students from the University of Rhode Island, the University of Massachusetts, Oregon State University, the Woods Hole Oceanographic Institution, the University of California at Santa Cruz, the University of Hawaii, SubChem Systems, NAVAIR's Electro Optic and Special Mission Sensors Division at Patuxent River, MD, NAVSEA's Naval Undersea Warfare Center in Newport, RI, the Monterey Bay Aquarium Research Institute, and the University of California, Berkeley. As a part of our work, one of us (Holliday) , also served on the LOCO Scientific Steering Committee. We also coordinated the LOCO small boat operations for LOCO.

REFERENCES

Cassie, R.M. 1963. Microdistribution of plankton. Oceanogr. Mar. Biol. Ann. Rev. 1: 223-252.

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. 2009. Chapter 17 in The Future of Fisheries Science in North America, Beamish, Richard J. and Rothschild, Brian J. (Eds.), Springer-Verlag Fish & Fisheries Series, Vol. 31: 293-311, doi:10.1093/icesjms/fsp127.

Jones, R. 1973. Density dependent regulation of the numbers of cod and haddock. Rapp. P.-v. Reun. Cons. perm. int. Explor. Mer 164, 156–173.

Lasker, R., 1975. Field criteria for survival of anchovy larvae: The relation between inshore chlorophyll maximum layers and successful first feeding. Fish Bull. 73: 453-462.

Mullin, M.M. and Brooks, E.R., 1976. Some consequences of distributional heterogeneity of phytoplankton and zooplankton. Limnol. Oceanogr. 21: 784-796.

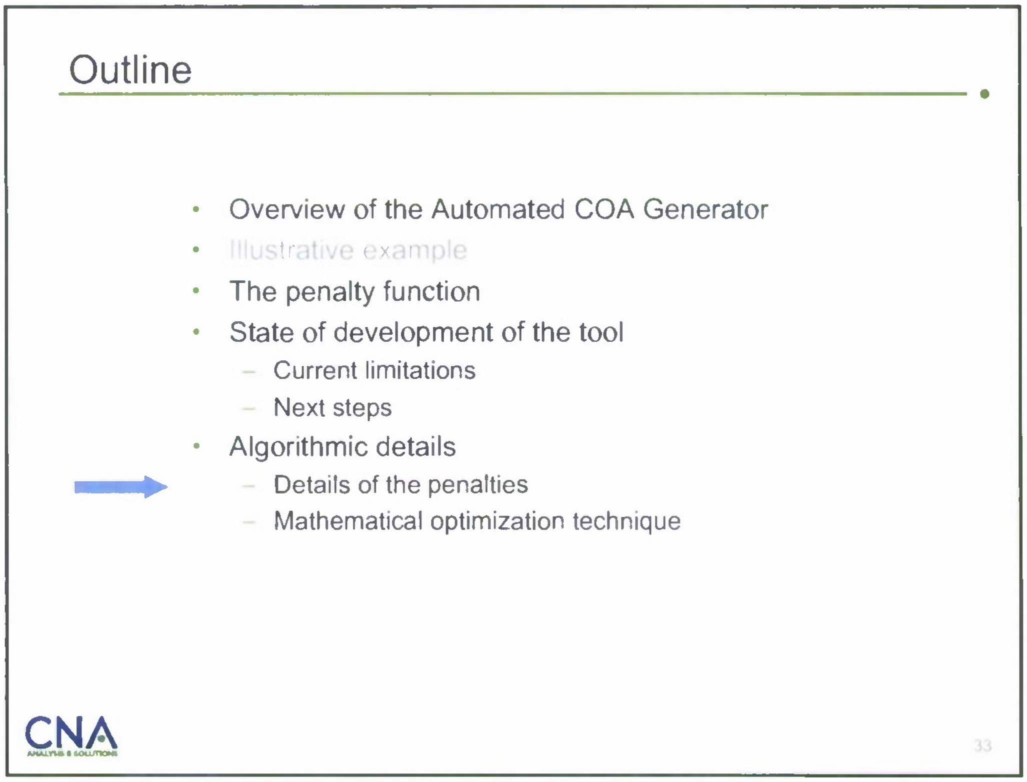
Steele, J.R. 1976. Spatial patterns in plankton communities. Plenum Press, New York, 470 pp.

PUBLICATIONS

Holliday, D.V. Technology for Evaluating Marine Ecosystems in the Early 21st Century. Chapter 17 in *The Future of Fisheries Science in North America*, Beamish, Richard J. and Rothschild, Brian J., Eds. Springer-Verlag Fish & Fisheries Series, Vol. 31: 293-311, doi:10.1093/icesjms/fsp127. [published, refereed.]

Holliday, D.V., P.L. Donaghay, C.F. Greenlaw, J.M. Napp, and J.M. Sullivan. 2009. High-frequency acoustics and bio-optics in ecosystems research. ICES Journal of Marine Science 66: 974-980, doi:10.1093/icesjms/fsp127. [published, refereed.]

Holliday, D.V., C.F Greenlaw and P.L. Donaghay. Acoustic scattering in the coastal ocean at Monterey Bay, CA USA: Fine-scale vertical structures. Continental Shelf Research. [in press, refereed.]



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The E multipliers are used by the algorithm for "equalization." The need for equalization arises because the various kinds of penalties have differing mathematical expressions used for calculating their numerical contributions to the overall penalty. Assume for the moment that all the input weighting factors were set equal to 1 by the user, and that the normalization factor, *N*, (discussed below) were also set to 1. The equalization factors are chosen automatically by the autoscheduler so that a one-day infraction affecting any term in the penalty function will produce one unit of penalty from that term. The rationale for this is that the optimization algorithm may be confronted with a choice between incurring a penalty in either one of two terms. For example, either exceed the allowed deployment length by a day in one case, or allow a one-day shortfall in coverage in one theater. With equalization handled properly and equal weighting factors for these two terms, this choice should be a toss-up. If one term has a lower weighting (importance), the optimization algorithm should choose to accept the penalty in that lower-importance term.

The normalization factor *N* is a common multiplier applied to all the terms in the objective function. Because the same multiplier *N* is applied to all the penalty terms, their relative magnitude is unaltered and this normalization has no material effect on the optimization. At the start of an autoscheduler run, the

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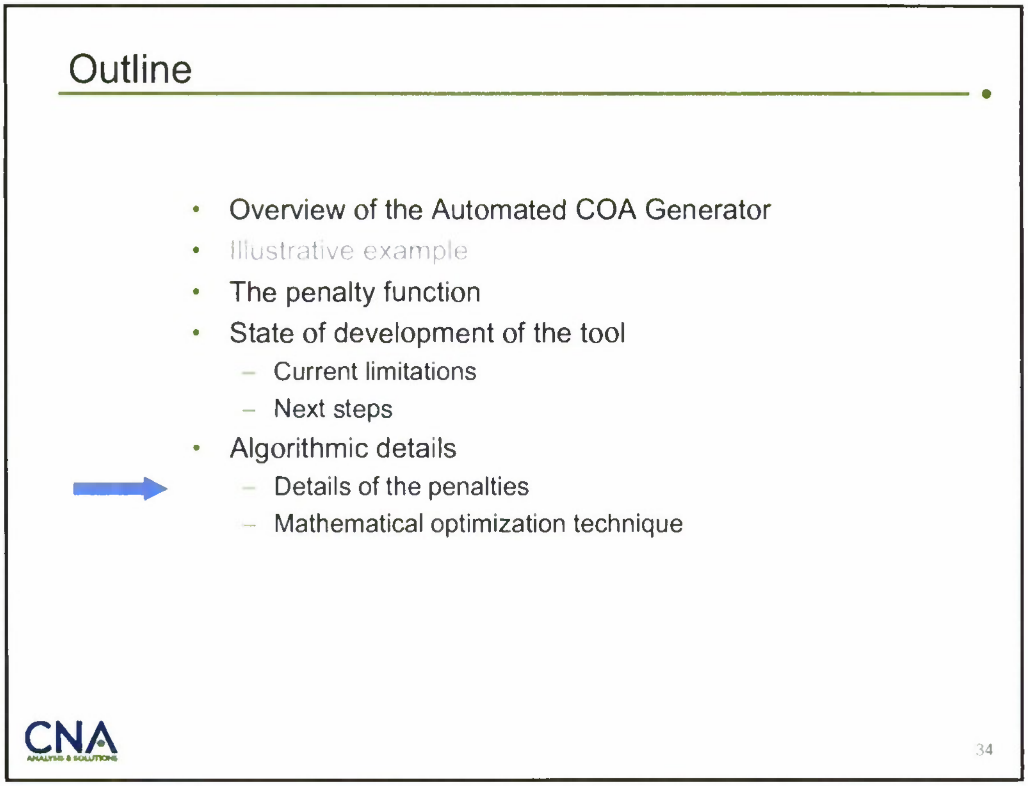

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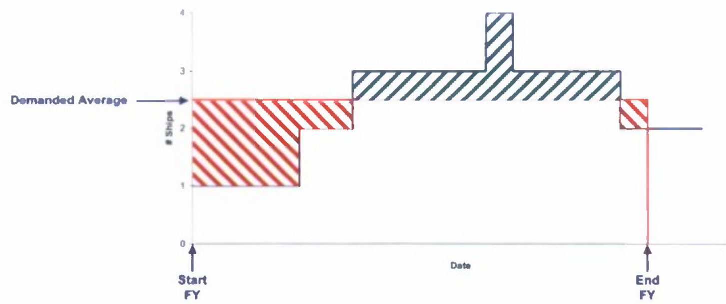
algorithm constructs a "starting schedule," which is generally a very poor schedule COA. The algorithm chooses N at the outset to set the starting value of the overall penalty function for that starting schedule to a numerical value of 1000 (in arbitrary units, which we call "degrees"). As the optimizer runs, it finds smaller values of the penalty function, hopefully much smaller, by improving the schedule. The reason for performing the normalization is that doing so allows the computerized algorithm to internally handle contributions to the penalty function of a moderate and predictable numerical size.

The penalty function: average AOR presence

We incur a penalty for any year in which the average presence delivered falls short of the demanded average, A_{dmd}

$$F_{Average} = g_A NE_A \begin{cases} N_{days}(FY)A_{dmd}(FY) - \sum_{i_{day} \in FY} S_{AOR}(i_{day}), & \text{if positive} \\ 0, & \text{otherwise} \end{cases}$$



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Average presence refers to the average number of ships that are present in a given AOR during a time period. The time period for which the average gets tabulated is usually a fiscal year (FY). However, if the scheduling time window begins or ends part way through an FY, the average can be tabulated for a fraction of a year. What the algorithm does is find the total number of ship-days of presence provided by a candidate schedule during the FY (or shorter period) and compares that to the demanded number of ship-days. The penalty is proportional to any shortfall. Therefore, days when the delivered presence exceeds the demanded level (cross-hatched in green on this slide) can offset other days during the FY when the delivered presence falls short (red cross-hatching). Notice that this formulation is insensitive to the time distribution of presence within the FY.

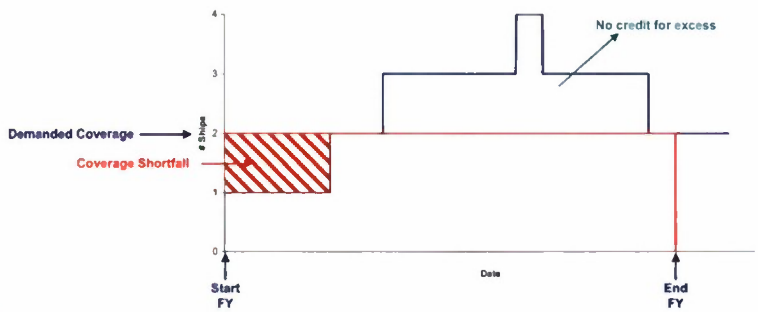
Penalties are computed separately for each FY, so a shortfall in one FY cannot be offset by a surplus in delivered presence for another FY.

In the formula on this slide, $S_{AOR}(i_{day})$ represents the number of ships present in the given AOR on date i_{day}. A_{dmd} is the demanded average presence level, and $N_{days}(FY)$ is the number of days in the fiscal year (or portion of a fiscal year).

The penalty function: AOR coverage

We incur a penalty for any day on which the theater presence delivered falls short of the demanded coverage level, C_{dmd}

$$F_{Coverage} = g_C NE_C \sum_{i_{day} \in FY} \begin{cases} C_{dmd}(FY) - S_{AOR}(i_{day}), & \text{if positive} \\ 0, & \text{otherwise} \end{cases}$$



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Coverage refers to the number of days that a candidate schedule covers to a user-stipulated level. In the example shown here, the demand is for two ships to be present in the AOR. The penalty is proportional to the number of ship-days of shortfall (cross-hatched in red), relative to that coverage demand. In this case, the timing of ship presence does matter: excess presence in the AOR at one point during the FY does not offset a coverage shortfall at some other time during the FY.

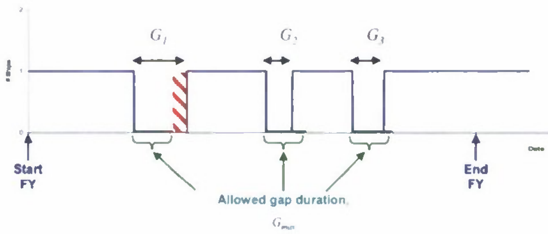
If the user asks for a fractional coverage less than 1.0, such as $C_{dmd}(FY) = 0.5$, then the demand is for half of the days in the FY to be covered by at least one ship.

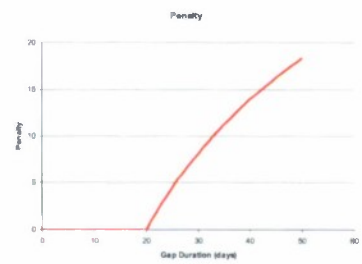
If the demanded coverage has a fractional part but is greater than 1.0, for instance $C_{dmd}(FY) = 1.5$, how does the algorithm interpret the demand? It takes the minimum acceptable presence on any given day to be 1 ship, assessing a penalty for any day having no ship present, and it interprets the demand to mean that at least half the days in the FY should have two (or more) ships present. A penalty is therefore also incurred to the degree that less than half the days have a second ship present.

The penalty function: AOR coverage gaps

We incur a penalty for any gap in theater presence longer than a user-specified maximum, G_{max}

$$F_{Gaps} = g_G NE_G \sum_{\text{Gaps}} \begin{cases} \ln\left(\dfrac{G_i}{G_{max}}\right), & \text{if positive} \\ 0, & \text{otherwise} \end{cases}$$





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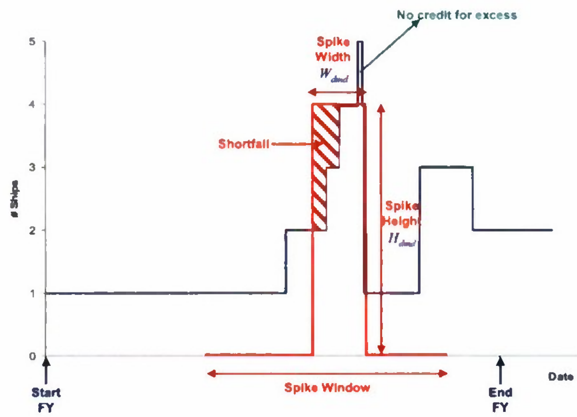
Apart from specifying an overall level of coverage desired in an AOR, there may be a limit on the number of consecutive days on which it is acceptable to have no coverage. The algorithm looks through the sequence of days that make up an FY and identifies sequences of days having no ship presence. This creates a list of gap durations, G_1, G_2, G_3, … . Each of these must be compared to the acceptable maximum gap length, G_{max}, and a penalty is applied for any gaps longer than G_{max}. In the example shown on this slide, G_1 exceeds G_{max}, leading to a penalty, while G_2 and G_3 are short enough that they incur no penalties.

The graph illustrates a case in which the user has specified a G_{max} value of 20 days.

The penalty function: spikes in AOR presence

Within a user-specified window, we seek a spike in AOR presence of height H_{dmd} and duration W_{dmd}. We incur a penalty proportional to the degree to which we fall short of delivering what is demanded.

$$F_{Spikes} = g_S N E_S \min_{j_{day} \in \text{Window}} \left[\sum_{i_{day}=j_{day}}^{j_{day}+W_{dmd}-1} \begin{cases} H_{dmd} - S_{AOR}(i_{day}), & \text{if positive} \\ 0, & \text{otherwise} \end{cases} \right]$$



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The presence demand signal may include a "spike" within a user-defined time window, which may be a full FY or a portion of the FY. The spike is described by a height (i.e., number of ships called for) H_{dmd} and a width (i.e., duration of the spike), W_{dmd}. In the example shown here, the spike height is $H_{dmd} = 4$. The red rectangle in this example represents a "template" for the spike that is demanded, having a height equal to H_{dmd} and a width equal to W_{dmd}.

For the template position shown here, the penalty incurred is proportional to the shortfall area, cross-hatched in red. This template could be positioned earlier or later, as long as it remains within the larger spike time window. The positioning shown here, however, minimizes the shortfall; any other template position leads to a larger shortfall and so a larger penalty. What the algorithm does is find the template position that minimizes the shortfall. In other words, it finds the portion of the schedule (within the spike window) that delivers or comes closest to delivering what is demanded.

The penalty function: dwells

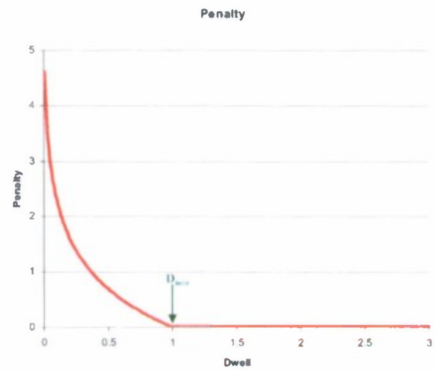
We incur a penalty for dwells less than a user-specified minimum, D_{min}

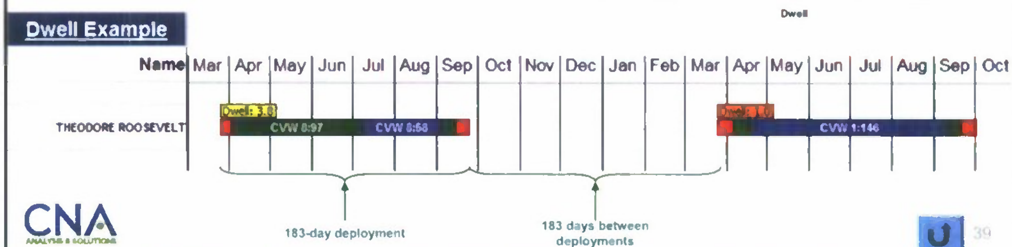
$$F_{Dwells} = g_D NE_D \sum_{Dwells} \begin{cases} \ln\left(\frac{D_{min}}{D_i}\right), & \text{if positive} \\ 0, & \text{otherwise} \end{cases}$$

where dwell ratio is defined as:

$$D = \frac{\text{Time between deployments}}{\text{Length of previous deployment}}$$

Generally, the minimum dwell, D_{min}, is 1.0, based on PERSTEMPO rules.





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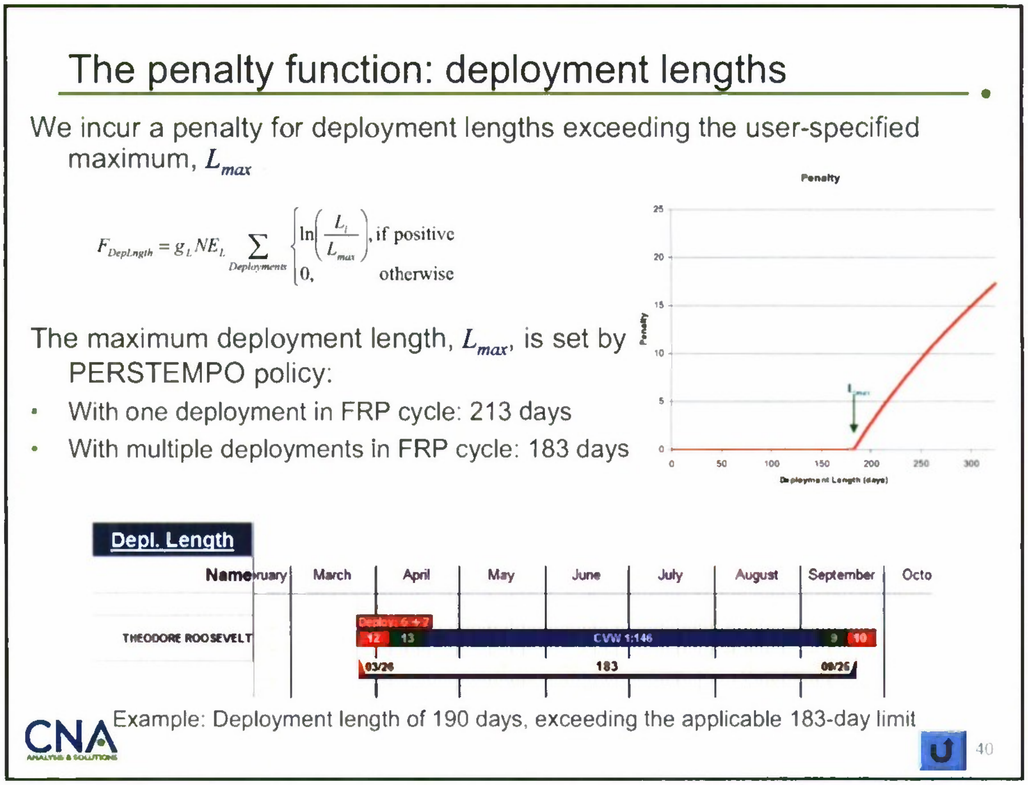
As we discussed earlier (slides 15 and 17), dwell is defined as the ratio of the interdeployment period for a ship to the length of the prior deployment. The example on this slide shows a six-month (183-day) deployment, followed by a non-deployed period of equal length. This implies a dwell of 1.0, as displayed at the start of the next deployment.

The PERSTEMPO policy [1] sets a minimum for dwell of 1.0, except for ships that are part of the Forward Deployed Naval Force (FDNF). Therefore, this example is a case where the dwell is exactly at the minimum allowed by the PERSTEMPO policy. Infrequently, lower dwells are seen in the fleet schedules. Because that represents a PERSTEMPO violation, leadership approval is required in such situations. Correspondingly, the autoscheduler is designed to apply a substantial penalty for even a modest dwell violation, so that the schedule COAs it generates contain dwell violations only infrequently, but such dwell violations are not entirely prevented.



Deployment length is defined as the number of days from departure from homeport until return, inclusive. As mentioned earlier (slide 17), it is limited by PERSTEMPO policy. As in the discussion of dwells, exceeding the allowed deployment length is a PERSTEMPO violation, and leadership approval is required. Again, the autoscheduler is designed to apply a substantial penalty for even a modest deployment length violation, and the schedule COAs it generates contain such violations only infrequently.

The PERSTEMPO policy sets a maximum for deployment length of 213 days, if the ship makes only one deployment during its FRP cycle. If the ship makes multiple deployments during the cycle, the maximum is 183 days. We note again that these limits do not apply for ships that are part of the FDNF.

The example shown here is a deployment lasting 190 days. Presuming this to be part of a cycle having another deployment, we have L_{max} = 183, so that this deployment exceeds the PERSTEMPO limit by 7 days.